A Nuclear Excavated Harbor Design

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CHAPTER I

INTRODUCTION

The use of nuclear explosives for the excavation of harbors offers tremendous opportunities to create greatly improved and much needed harbor facilities that will benefit all of mankind. Present-day harbors have two distinct deficiencies: 1) there are not enough of them to provide for mankind's demands and 2) not all of them are located in the most desirable places. There are areas of the world that could realize great economic development with adequate harbor facilities. Such areas include the west coast of Africa, Australia, and South America.[1] These coasts, for example, adjoin areas of extensive mineral resources and some of the world's most fertile fishing grounds. Well-placed harbors could open these regions to development, but in many cases only nuclear explosives are powerful and economical enough to do the required work.

There are, however, limitations on the use of nuclear explosives for construction purposes. A nuclear detonation near the ground surface involves much more than merely producing a crater or mound of rock. The extent and safety implications of the radioactivity, airblast, and ground shock effects, which are by-products of nuclear cratering detonations, must be clearly understood and analyzed prior to a nuclear detonation. Since nuclear explosives have not, to date, been directly applied to creating a harbor, some research in regard to radiation hazards is still required. Nevertheless, sufficient data does exist from other nuclear explosive projects to permit an analysis of the hazards that can be expected. Radioactivity, airblast,

and ground shock effects will impose definite limitations with regard to the proximity of the proposed project site to population centers. By employing adequate safeguards to protect man and his environment from any possible hazards, nuclear explosives can be used for large scale harbor excavation projects.

Nuclear construction of harbors will open a new field of technology for mankind. It will be possible to design and site many harbors that will best suit his needs without worry of natural limitations or prohibitive costs. These new harbors, created with nuclear energy, can be built with a flexibility of design that will provide safe refuge for ships of all sizes. This is in contrast to many of the present harbors of the world that nature, at times renders unsafe for navigation.

The basic concept of nuclear excavation involves the subsurface detonation of a nuclear explosive to break up and eject large quantities of rock and/or soil. The primary advantage in using nuclear methods rather than conventional methods in the construction of a harbor is economy.[2] The nuclear cratering experience to date indicates that there is a significant potential for using nuclear explosives to accomplish large scale construction projects at considerable savings in cost and time as compared to conventional construction techniques.

A proposed harbor design is presented here with an analysis of the related safety considerations. Chapter II contains a brief outline of the various steps required in planning a harbor and how nuclear explosives may be applicable in harbor construction.

Chapter III discusses the detailed and exhaustive investigations that must be conducted prior to and after a nuclear detonation in order to protect both man and his environment from any harmful effects. The geometric configuration of the proposed harbor is presented in Chapter IV. The possible radiation hazard and the ground shock and airblast effects are analyzed in Chapters V and VI, respectively. Chapter VII contains the costs associated with the size of explosive charge and its emplacement in the ground. The summary and conclusions based on this analysis are contained in Chapter VIII.

CHAPTER II

HARBOR PLANNING AND NUCLEAR CONSTRUCTION

A. Harbor Planning and Development

The history of harbor construction dates back to ancient times, perhaps as early as 3500 B.C.[3] The harbor construction technology which has evolved through the centuries has been based on some fundamental concepts such as availability of manpower and/or equipment, and the utilization of natural formations where possible to reduce cost. The utilization of nuclear explosives for harbor excavation will not change the overall systematic procedure of harbor construction but may allow more flexibility in siting. No longer will areas be discounted because of geological formations that would make the cost of excavation prohibitive. Close proximity of population centers, however, may preclude the use of nuclear explosives. For large projects, labor and equipment considerations will be of less importance in determining the harbor location. More of the specific advantages of utilizing nuclear explosives for harbor excavation are discussed in a later section.

The systematic procedure of constructing harbors is well established, therefore, only a brief outline is presented. A harbor is a water area partially enclosed and so protected from storms as to provide safe and suitable accommodation for vessels seeking refuge, supplies, refueling, repairs or the transfer of cargo.[3] Harbors may be classified as: 1) natural, semi-natural or artificial, and 2) as harbors of refuge, military harbors, or commercial harbors.

Attention here will be focused on construction of artificial or semi-natural harbors.

The basic procedure in the planning and development of a harbor can be catagorized as follows:[3]

1. Project Proposal. The decision to build a port, and its location, generally will be determined by factors having to do with:

a) its need and economic justification; b) prospective volume of seaborne commerce; and c) availability of inland communications by both land and water.

2. Preliminary Planning. After general location of the harbor has been established, as well as its principal use, the next step will be to make preliminary studies and layouts of the port in preparation for making a complete site investigation to gather all the information which will be needed in making the final design of the port.

Information for this preliminary planning in the United States can be obtained from such sources as: U. S. Department of Commerce, The Navy Department, The U. S. Corps of Engineers. All of these agencies have surveyed a great many of our navigable waters. Most charts of this survey data can be obtained from the U. S. Government Printing Office. These charts give information on the depth of water, bottom features and range of tides. Meteorological data on winds, temperatures, and rainfall are published by the U. S. Weather Bureau.

If the port is located in some part of the country or world where this information is not available, it will be

necessary to make a preliminary site reconnaissance. Aerial photographs are a quick and convenient way of obtaining topography.

3. Harbor Layout. This step is to make preliminary studies of the harbor and port layout. This will usually be supplemented with approximate cost estimates based on certain assumptions which will have to be verified when making the site investigation.

4. Site Investigation. Unless the site is fixed by specific requirements of the port, several possible locations of the harbor will have to be studied to determine the most protected location. The location selected should involve the least amount of dredging and the most favorable bottom conditions as well as a shore area suitable for the development of the terminal facilities.

It may be impossible to fulfill all of the above conditions, as one or more may predominate to the exclusion of others. As mentioned before, nuclear explosives will offer a great degree of latitude in siting. As an example, consider the nuclear crater, which, in addition to creating an excavation of the required depth, results in the formation of a crater lip which may function as a breakwater to protect the harbor area from wave action. Other advantages of nuclear explosives as they relate to siting flexibility are discussed later.

5. Size and Shape of Harbor and Turning Basin. The number and size of ships using a harbor will determine its size to a large

extent, but existing site conditions will also have an important influence. Generally speaking, unless the harbor is a natural one, its size will be kept as small as will permit safe and reasonably comfortable operations to take place.

6. Type, Location and Height of Breakwaters. Breakwaters are required for the protection of artificial and semi-natural harbors. Their location and extent will depend upon the direction of the maximum waves, the configuration of the shore line, and the minimum size of harbor required for the anticipated traffic in the port. Rarely will a location be found where the waves are from one direction only. Generally, it will be better in a harbor having two openings for the ships to enter from the direction of the minimum wind and waves and to leave toward the direction of the maximum wind and waves. This is because upon leaving a harbor, the ship usually has the freedom of open water in which to maneuver, whereas upon entering the harbor, it must approach the docks at a reduced speed.

7. Location and Width of Entrance to Harbor. In order to reduce the wave height within the harbor, entrances should be no wider than necessary to provide safe navigation and to prevent dangerous currents when the tide is coming in and going out. The entrance width should be in proportion to the size of the harbor and the ships using it. In general, these entrance widths will vary from 300 to 800 feet.

8. Depth of Harbor and Approach Channel. For ideal operating conditions, the water in the approach channel, in the entrance

and in the harbor should be of sufficient depth to permit navigation at the lowest low water when the ship is fully loaded. This depth must include an allowance for the surge of the ship, which is about one-half the wave height, the out of trim or squat when in motion, and from 2 to 4 feet clearance under the keel, the larger figure being used when the bottom is of hard material such as rock.

Until recent years, a harbor depth of 35 to 40 feet would have taken care of most ships. With the advent of the supertanker, however, with a dead-weight tonnage of 84,000 to 500,000 tons and a draft of 47 to 50 feet, new problems are presented in harbor design. To date, the approach to these problems has been one of the following:

a. The use of submarine lines and an offshore anchorage in water 55 to 60 feet in depth.

b. The transfer of part of the load to smaller tankers in deep water.

c. The construction of a special deep-water unloading terminal. Here again, there exists a tremendous opportunity in the application of nuclear explosives for an economical solution to these problems.

9. Construction of Related Harbor Facilities. The last step in the sequence of designing and building a harbor is the provision for all related facilities. These related facilities include docks, piers, warehouses, navigation lights and related markings, bulk storage facilities, terminal buildings and other miscellaneous buildings. The area comprising a port

or falling within its jurisdiction will vary with the nature and tonnage of the cargo to be handled and the services to be provided at the port. The area may vary from less than 1 square mile to over 1,400 square miles as for the Port of New York.

Probably no single factor has contributed so much to placing the design of harbors on a sound engineering basis as has the testing of hydraulic models. The hydraulic laboratory of the Waterways Experiment Station at Vicksburg, Mississippi, and The NEYRPTIC Hydraulic Laboratory at Grenoble, France, have performed numerous model investigations on outstanding harbors. This technology should supplement the nuclear cratering technology, as it applies to harbor excavation, which is being developed by the Atomic Energy Commission under its Plowshare Program.

B. Engineering Characteristics of Nuclear Excavations

Nuclear excavation involves the detonation of one or more nuclear charges to provide a crater or a ditch for the appropriate purpose. The Atomic Energy Commission has conducted several tests under the Plowshare Program in developing the phenomenology of nuclear craters. These tests have helped to answer the following questions[5] which are necessary for the development of this technology:

1. How does crater size depend on geologic properties?
2. Can data on crater size, seismic effects, acoustic waves, and radioactivity distribution of low-yield experiments be extended to yields in the megaton range?
3. How do nuclear charges in a row interact?

In order to become proficient at excavating in various earth materials with nuclear energy, the mechanisms of excavation at very large yields must be known. Specific information will be needed which includes the optimum depth of burst (D.O.B.) for various media, proper spacing of line charges, and the spatial distribution of excavated material.

The extensive testing already conducted by the AEC has provided a great deal of information on cratering techniques and the characteristics of nuclear excavations. When a nuclear charge is detonated at or near the ground surface, it produces a crater by the tremendous energy release of the explosion by the processes of crushing, compaction, plastic deformation spalling and gas acceleration.[2] The pressures (up to millions of atmospheres) generate a shock wave which propagates as a high pressure discontinuity. This shock front transfers energy to the medium and, in turn, alters the physical characteristics of the medium. The pressure spectrum in the immediate vicinity of the explosion is sufficiently high to vaporize and melt the material as the shock wave passes through it. When the pressure level exceeds the dynamic crushing strength of the material, there results crushing, heating and physical displacement. This entire process lasts for only a fraction of a second.

The next important crater-producing process is designated as spalling. When the compressive wave which propagates outward from the detonation encounters the ground surface, two reflected pulses are generated - a tensile pulse and a shear stress pulse. The tensile pulse is able to break off a mass of material and impart a characteristic velocity due to the energy trapped in it. Successive

masses of material will break away until a plane is reached where the tensile stress becomes smaller than the tensile strength of the material. Spalling of the free surface is one of the most important phenomena in cratering and appears to be the dominant process in a shallow explosion.

The gas acceleration is a long-period process which imparts motion to the material around the explosion by the adiabatic expansion of gasses trapped in the cavity produced. This gas imparts an appreciable acceleration to the overlying material during its escape through cracks extending from the cavity to the surface. Great quantities of the overlying material will fall back into the cavity (which help to trap most of the radioactive material) and the rest is thrown clear and forms the crater lip. The size of the crater produced depends upon the yield of the explosion and the depth of burst.

In order to predict the dimensions of a crater and the effects associated with a nuclear explosive, scaling laws can be employed which relate the effects of small cratering explosions to those of larger yield. The AEC has made great strides in developing these scaling laws. The Plowshare Program has carried out experiments[6] with chemical explosives ranging from 250 lbs. to 500 tons. These detonations were carried out in single events with spherical configuration and centrally ignited to simulate nuclear explosives. Scaling laws were then established for chemical explosives over the experimental range of yield use, which covers a factor of 4000 in energy. Nuclear explosive tests were then conducted and the results were applied to these scaling laws. These relationships showed the

crater diameter and depth to be proportional to $W^{1/3.4}$, where W is the yield in kilotons (kt), and the crater dimensions are also dependent on the depth of burst.

Although there is presently much information available on nuclear cratering technology, future experiments will be required to provide data on scaling criteria for larger yields, crater dimensions in various hard rocks (where most practical civil applications will be considered) and the features of nuclear row charges. It should also be pointed out that more information is required on underwater cratering such as the effect of a large water layer over the detonation area and the stability of crater slopes so produced. Detailed plans were developed to conduct a major underwater excavation experiment (CHARIOT) in 1960 on the northwest coast of Alaska.[8] This plan was to construct a harbor and entrance channel using one 200-kt and a row of four 20-kt explosions. This would have been an excellent experiment and the first using a row of nuclear charges to make a channel. However, it was successively delayed throughout the nuclear test moratorium and now has been largely overtaken by factors such as public opinion. Much valuable information has been obtained on the features of a nuclear row charge detonation from project BUGGY[4] (March 1968). This test consisted of the simultaneous detonation of five 1.2-kt devices, resulting in a crater 900 feet long, 250 feet wide and 60 feet deep.

From this brief discussion of the characteristics of nuclear excavated craters, it can be seen that nuclear energy can provide a tremendous improvement to man's construction capabilities. Nuclear energy will enable man to accomplish construction projects never

before thought possible. Of course, careful planning and the strictest procedures will have to be employed and followed when undertaking an excavation project utilizing nuclear explosives in order to ensure that there is no undue risk to the health and safety of the public. Some of the hazards associated with the use of nuclear explosives such as shock wave damage and radiation fallout are discussed in later sections.

C. Nuclear Explosive Applications To Harbor Construction

The greatest advantage of using nuclear explosives for harbor excavation is the flexibility provided in siting. This is due to the fact that nuclear explosions can produce an exonomical excavation in hard rock as well as in soft sediment.[4] With this added flexibility, harbors can be located without geologic restrictions and it will not be necessary to depend on natural formations to make them economical or navigationally safe. Many harbors of the world today are located at the mouth of a large river and consequently are plagued by sedimentation which contributes greatly to high maintenance costs. With the freedom of siting offered by nuclear explosives, harbors could be built that are virtually free from sediment.

Without question, sedimentation is the single most important factor in the configuration, limitation of draft of ships, and cost of harbor development and maintenance.[9] This then points up another possible advantage of the nuclear constructed harbor: that even if the initial costs of the nuclear harbor are higher, it may well be more economical in the long run when considering this increased maintenance cost for dredging.

Conventional harbors may also have other serious defects. The entrances to many harbors are often impassable because of the breaking swell in the outer harbor. Ice and log flotsam, nipa rafts (floating vegetation), tidal floods, surging and seiching (surface oscillations) are other troublesome, dangerous or crippling conditions of conventional harbors. Ice forms more readily on fresh or brackish water than on sea water because of the stabilities and temperatures involved. Floods can carry ships out of control and rapidly alter channels. An inspection of the harbors of the world reveals few that are immune to many of these undesirable characteristics. There are, however, several naturally occurring harbors of the world that are free from many of these ills. These harbors can be studied to determine their characteristics, and with the use of nuclear explosives it may well be possible to incorporate their best features in future harbor construction.

Other steps in the planning and development of a harbor that will be influenced by the use of nuclear explosives will be the harbor layout and site investigation. No longer will the natural formations dictate the harbor layout nor will the bottom geology play such an important role in site selection. As was previously mentioned, the nuclear excavated crater embodies a lip that will assist in acting as a breakwater for the harbor protection. This crater lip may suffice as a breakwater or may be incorporated as the foundation for a breakwater. In any event, this lip will play an important role in the design and construction of breakwaters.

CHAPTER III

SAFETY CONSIDERATIONS AND SITE INVESTIGATIONS

A. Safety Programs

Prior to assessing the engineering feasibility of using nuclear explosives for construction at a particular site, certain elements must be thoroughly investigated. Nuclear explosives possess the capability of drastically altering the physical, chemical, and biological properties of the surrounding media, including the plant and animal life. It is, therefore, necessary to know precisely what effects will be caused by a nuclear detonation in order to ensure that there will be no undue risk to the health and safety of the public.

The Nevada Operations Office of the Atomic Energy Commission has at present a prime responsibility for the execution and safety of all underground nuclear detonations carried out by the United States Government.[10] The detonation of a nuclear device can never be assumed to be free from danger or risk. A definition of safety which reflects the philosophy of the Nevada Operations Office is:

> A nuclear device can be detonated safely when it is ascertained that the detonation can be accomplished without injury to people, either directly or indirectly, and without unacceptable damage to the ecological system and natural and man-made structures.

Potential hazards should be investigated and plans and safety procedures put into effect well before and continued long after a nuclear detonation. This is necessary to assure the safety of all personnel and property both on and off site. The NVOO has developed two programs to ensure that all detonations are conducted in

accordance with the concept. The first program is associated with the safety measures taken at the time of a detonation. The second program involves the long-range studies and is a continuous effort to expand the understanding of event-related phenomena. The specific safety programs carried out by NVOO include:

1. Geologic considerations
2. Hydrologic considerations
3. Radionuclide migration in ground water
4. Ground motion and structural response
5. Mine and well inspection program
6. Meteorology considerations
7. Bioenvironmental safety

The reader is referred to the "Technical Discussions of Offsite Safety Programs for Underground Nuclear Detonations" NVO-40, May 1969[10] for further understanding of the scope of these safety programs. Special emphasis should be placed on the area of radiological safety since this is the subject about which the least information is known in terms of long range effects on man. It is difficult to predict the distribution of radioactive particles or the dose levels that result from a nuclear explosion. Particles can collect on dust and be carried by the wind, or they can enter the ground water where they will be carried away in solution. Because release of radioactivity at any level is a potential hazard, there must be continuing efforts to reduce to a minimum the quantities of radioactivities produced and released to the biosphere. This can be accomplished in several ways, such as; development of cleaner devices (lower fission/fusion ratio), entrapment of the radioactivity underground such as in an excavation explosion,

detonating the device when winds are away from populated areas, and evacuation of possible hazard areas until dilution and decay have reduced the radioactivity level.

Only a small fraction of the total radioactivity escapes from the explosion of a nuclear charge which is buried at sufficient depth. Experiments suggest that nearly optimum cratering efficiency can be attained at D.O.B.'s sufficient to contain over 95% of the gross radioactivity. In addition, almost all the radioactivity that escapes adheres to fairly large particles which fall out locally and hence do not contribute to world-wide contamination. From the technological viewpoint, scientists are convinced that, while radioactivity cannot at present be completely eliminated from nuclear cratering explosions, it can be controlled to the extent that radioactive hazards need not be an obstable to the industrial exploitation of this technique.[6]

B. Site Characteristic Investigation

In order to ensure a successive safety program and obtain a reliable engineering feasibility evaluation that will lead to an economical project design, several categories of on-site data are required.[7]

1. Topography. Topographic data are needed as input to the design of a project. The topography may affect the project location, orientation, or alignment, or access requirements. The extent of detailed topographic coverage that will be required will depend primarily on the type of project.

2. Geology. The physical and chemical properties of the various geological formations are required to determine the cratering characteristics of the medium and to predict the specific radionuclides produced. Knowledge of the geological medium is also required to predict the characteristics of seismic propagation.
3. Hydrology. Hydrological studies are required to assess the effect on the regional drainage system, to determine flood control requirements, if pertinent, and to evaluate the impact of the local hydrology on the redistribution of radioactivity. Studies of the local precipitation are required to determine the extent of washing and leaching of debris and the transport of radioactive materials by water flow.
4. Hydrography. Bottom contours, bottom geology, littoral drift, and other hydrographic data are important in the design of a nuclear excavated harbor or canal project.
5. Meteorology. Meteorological data are required to determine the probable distribution of radioactive debris. This data, in the form of fallout patterns, when combined with hydrologic data, form the basis for the redistribution studies which are part of the bioenvironmental programs. This data is also important in predicting airblast over-pressures. Since this data leads to the specification of the exclusion area, it has a direct influence on the overall project cost.

6. Seismic Characteristics. Seismic propagation characteristics are required in order to define the areas in which the explosion-induced ground motion may constitute a hazard to existing structures. The results of these analyses are used, as are the meteorological data, as input to the overall project safety analysis to determine the maximum yield which can be safely and economically detonated.

7. Bioenvironmental Conditions.

   a. Terrestrial Studies. These studies will identify the major environmental features of the project site area that are of consequence to the safety of indigenous populations and natural resources located within potentially significant fallout areas. Included should be an analysis of any alteration to the land use of the area, and the resultant consequences to the animal and plant life. A study of the inhabitants diet and feeding habits of animals will provide information required to prevent any radionuclides from entering the food chain.

   b. Marine Study. Since a nuclear excavated harbor will involve interaction with the marine environment, studies must be made concerning the distribution of released radionuclides in the seas by ocean currents, the deposition of nuclides through sedimentation processes, and their redistribution and concentration by marine organisms, with special reference to species used by man.

8. Medico-ecology. These data are needed to assess the threats to health that may exist and will influence decisions on

where and how to displace indigenous personnel. Included would be data on human diseases, vectors and reservoirs of disease, venomous or otherwise harmful or dangerous forms of animal life, poisonous and hazardous plants, and other hazards of the environment of the on-site and resettlement areas.

CHAPTER IV

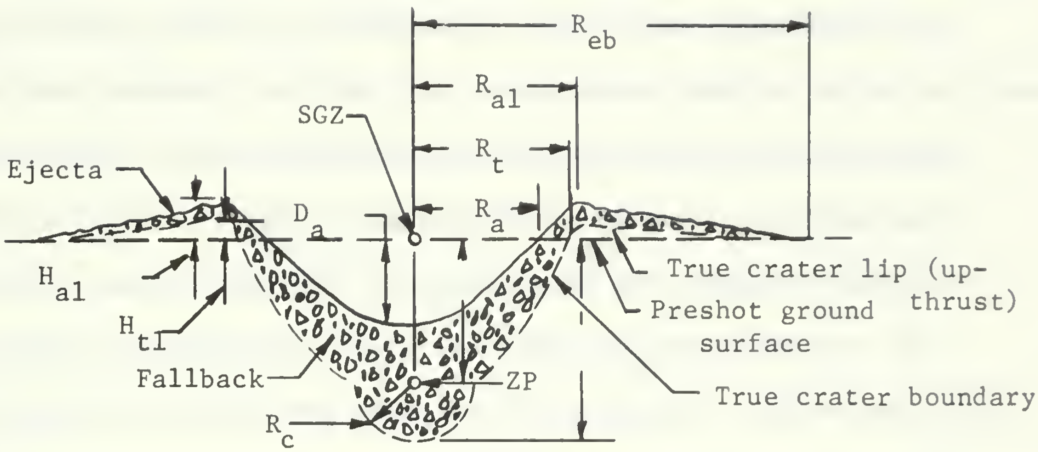
HARBOR DESIGN

As stated before, the number and size of ships using a harbor will determine its size to a large extent, but existing site conditions will also have an important influence. This design is based on a medium size harbor[3] that will accommodate approximately twelve large ships with a length of 800 to 1000 feet and the harbor depth will be no less than 200 feet. The harbor is designed for construction in a hard rock medium.

A. Nuclear Crater Dimensions

The basic concept of a nuclear excavated harbor involves the subsurface detonation of nuclear explosives to break up and eject large quantities of rock and/or soil in order to produce an excavation of the desired size. When a nuclear charge is detonated at or near the ground surface, it produces a crater with distinct characteristics as shown in Figure IV.1.

By carefully engineering the spacing and depth of burial of the nuclear explosives, an excavation of optimum size will be produced. In this design of a nuclear excavated harbor, advantage is taken of the characteristic crater lip to act as a breakwater that completely encloses the harbor for protection from the sea. The height of this crater lip and the diameter of the crater are of primary concern in determining the yield size to be used and the positioning of charges. The depth of a nuclear crater is approximately one-half the radius and for the yield sizes considered here, more than sufficient depth



Cross section of single-charge or row crater

R_a - Radius of apparent crater measured at preshot surface datum

R_{al} - Radius of apparent lip crest

R_{ab} - Radius of outer boundary of continuous ejecta

R_t - Radius of true crater measured on preshot ground surface

R_c - Radius of explosion-produced cavity

D_a - Maximum depth of apparent crater below and normal to preshot ground surface

H_{al} - Apparent crater lip crest height above preshot ground surface

H_{tl} - True crater lip crest height above preshot ground surface

DOB - Depth of burst (distance to ZP from SGZ, or from NSP for nonlevel surface)

ZP - Zero Point-effective center of explosion energy

SGZ - Surface Ground Zero (point on surface vertically above ZP)

D_t - Maximum depth of true crater below preshot ground surface

Figure IV.1 Dimensional data for single-charge and row craters[7]

for safe navigation will be achieved as shown later.

Figure IV.1 shows the cross section of a typical nuclear crater and the adjacent zones of disturbance. The crater dimensional data used in this analysis together with accompanying symbols and definitions are also shown. There are basically two approaches that have been developed to date for predicting crater dimensions.[7] One approach involves the use of computer calculations of the mound and cavity growth used in conjunction with a free-fall throw-out model. The second approach, and the one used in this analysis, involves empirical scaling relationships which relate the crater dimensions for some reference energy to crater dimensions for any energy yield.

The size of the crater produced for any given yield varies with the geologic medium in which the detonation occurs. In general, a detonation in dry soil will result in a crater that is the same depth but has a somewhat larger radius than the same detonation in hard rock, assuming both are detonated at the optimum depth of burial. For depths of burst slightly greater than optimum, the crater dimensions rapidly go to zero for hard rock.[4] This phenomena can be seen on the scaling curves in Figures A-1 and A-2, Appendix A.

For this analysis, a hard-rock medium is assumed as opposed to a soil medium. A rock medium is much better suited to nuclear excavation techniques than soil because of the more difficult problems of stability to be encountered in a soil excavation. The slope stability is of the utmost concern in a nuclear excavated harbor if the harbor is to withstand the errosive effects of the sea.

At present, some uncertainties exist as to the proper scaling of under-sea-floor explosions, however, it can be assumed that there

would be a wider, shallower crater formed than for the same detonation in dry land.[4] Since the scaling relationships used in this design are based on hard, dry rock, the predicted crater dimensions will be somewhat conservative.

From Figure A-1, a crater cross section can be developed for a one kiloton yield as shown in Figure IV.2. Dimensions shown in this figure are in feet/kiloton$^{1/3.4}$. Dimensions for craters produced by explosives with yields other than one kiloton can be obtained by multiplying the dimensions shown by the 1/3.4 power of the yield in kilotons. Table IV.1 lists the characteristic crater measurements of interest for various yields.

B. Harbor Configuration

From Table IV.1, a judgement can be made as to the appropriate explosive size, or combination of explosives, that would be required to produce any desired harbor dimensions, within the range shown. For comparison of various harbor sizes that will result, four cases of four charges each will be investigated. Each case consists of a larger charge, that is to create the outer turning basin of the harbor, and three smaller charges that will produce the docking area.

The charge emplacement pattern and the predicted harbor geometry are shown in Table IV.2 along with the dimensions associated with each case. The spacing of the B charges, of 1.2 times the apparent crater radius, is based on the conclusions of the plowshare experience to date with row charges. This spacing will result in a ditch with dimensions approximately equal to those expected from a single crater.[4] The apparent lip height (H_{al}) on the shore side, along the linear

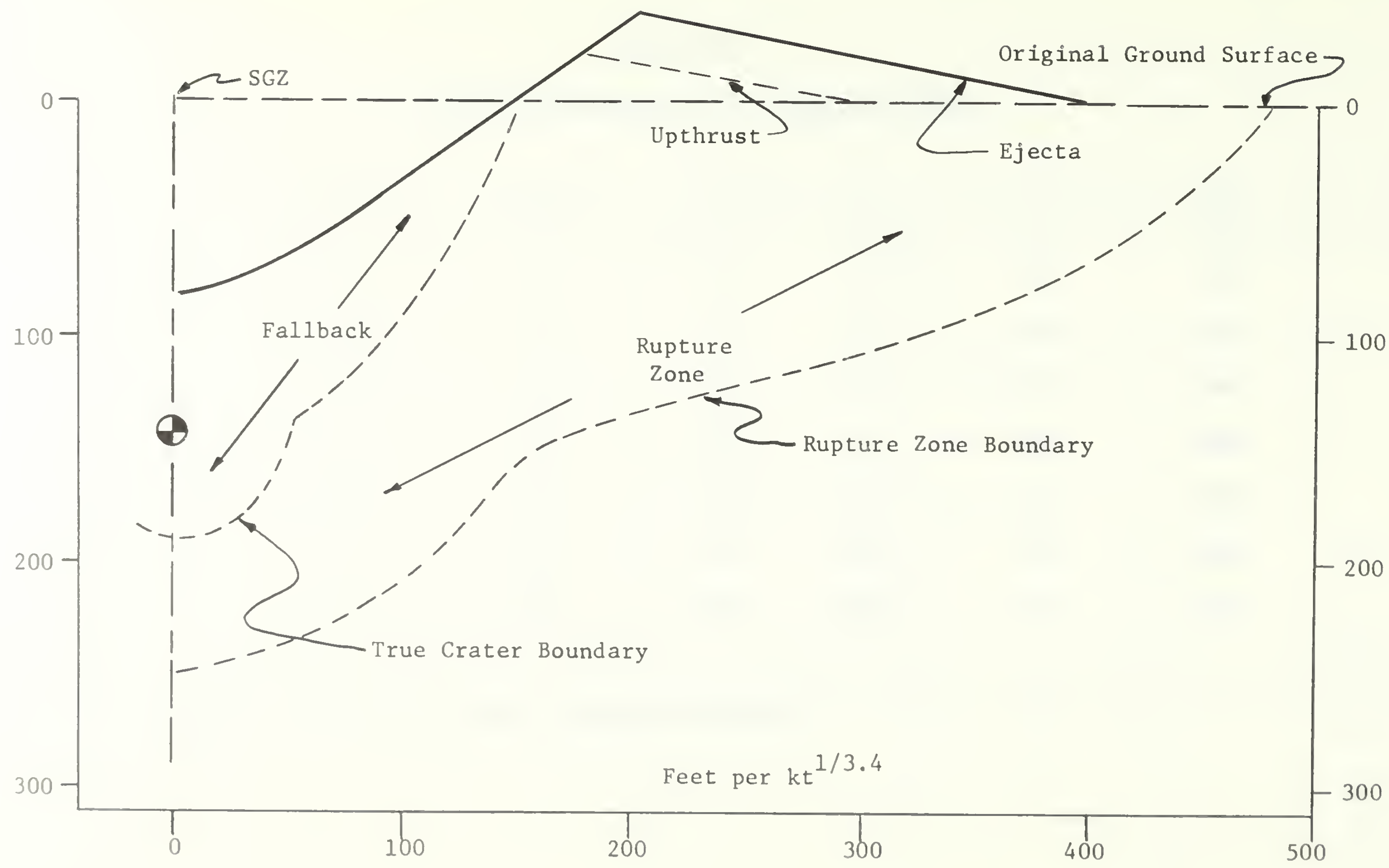


Figure IV.2 Cross Section of Typical Crater in Hard Rock Showing Zones of Disturbance[2]

Table IV.1

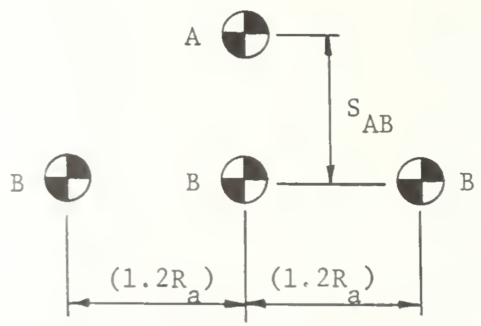
Crater Measurements* for Various Yields

Yield W(Kt)	$W^{1/3.4}$	D.O.B.	D_a	R_a	H_{al}	R_{eb}
1	1.000	145	88	150	40	400
10	1.968	285	173	295	78	785
100	3.875	560	341	580	155	1500
200	4.751	690	418	712	190	1900
500	6.220	900	545	928	248	2500
1000	7.627	1100	672	1140	305	3000
2000	9.352	1350	824	1400	374	3700

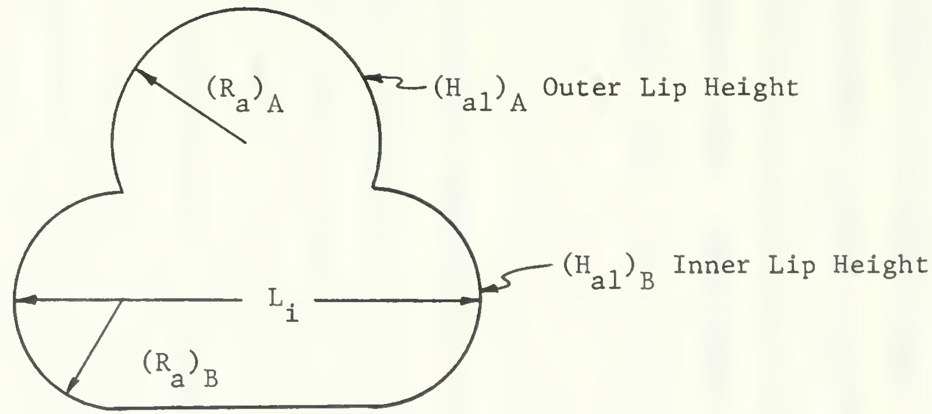
* All dimensions are in feet unless otherwise indicated

Table IV.2

Harbor Dimensions* for Various Yield Combinations



Charge emplacement pattern



Harbor geometry (plan view)

Case	Yield (kt)	S_{AB}	$(R_a)_A$	$(R_a)_B$	L_i	H_{al}
1	A 2,000 B 1,000	1,600	1,400	1,100	5,000	350 300
2	A 2,000 B 500	1,600	1,400	900	4,100	350 248
3	A 1,000 B 500	1,230	1,100	900	4,100	300 248
4	A 500 B 200	1,010	900	700	3,100	248 190

* all dimensions are in feet unless otherwise indicated

portion of the row crater, however, will be relatively higher than would result in a single charge. This is because the crater ejecta from the linear region of a row-charge are constrained to move laterally to the sides, rather than in all directions as in the case of a single crater. The length of this B charge row (L_i), called the inner harbor length, can be expressed by

$$L_i = 2(1.2 \times 150\ W^{1/3.4}) + 2(150\ W^{1/3.4}) = 660\ W^{1/3.4}$$

where W is the B charge yield in kilotons. The charges are to be located at a distance from the shore-line such that this ejecta lip can be used to backfill to the shore in order to provide area for ship off-loading, cargo handling and storage facilities.

The location of the larger A charge is such that the resulting harbor configuration will provide the optimum harbor area for ease of ship maneuverability, particularly for the piers near the ends of the harbor. This is done by requiring the circumference of the larger crater to intersect the smaller row crater at a point where the linear portion of the B charge row would begin. From the geometry of the figure then, this spacing can be determined by

$$S_{AB} = (R_a)_B + [(R_a)_A^2 - (1.2\ R_a)_B^2]^{1/2}$$

It is assumed that the net effect of these four charges will by such that there will be no mound of ejecta in the center of the harbor, or at least it will not form to within 100 feet of the surface. The fall-back in this area should settle toward the deepest parts of the A and B craters. Should this not be the case, and there results a mound in the center of the harbor, that would present a hazard to

navigation, it could easily be dredged away by conventional methods since it will be fall-back material that has been crushed and shattered by the explosion. Another alternative would be to excavate the harbor in increments. The B charges could be detonated in the first increment and then, at a later date when the radiation level has decreased to permit safe reentry, the A charge could be detonated. Safe reentry times are calculated in Section V.

The resulting harbor, scaled for Case 1, is shown in Plan View and Cross Section in Figures IV.3 and IV.4, respectively.

C. Throwout Lip and Slope Stability

The throwout lip is composed of the material which is ejected from the crater. This material falls on the upheaved true lip of the crater and out to a distance determined by the trajectories of the material. The combined true and ejecta lips make up the apparent lip of the crater. From Table IV.2, the apparent lip height for the 2 mt A charge of Case 1 is 350 feet. This is the predicted height above surface ground zero (ocean floor). From Figure IV.4, it is seen that this outer lip could be located as much as 5500 feet from the shore line. For an average bottom slope of 4%, the water depth at this point would be around 200 to 250 feet. The apparent lip then could be expected to rise above the mean water level by approximately 100 feet.

This hypothetical average bottom slope of 4% is used for illustration purposes only and is actually quite steep for very near the coast. In reality, the continental shelfs of most parts of the world do not fall off nearly this fast within a mile or two from the coast.

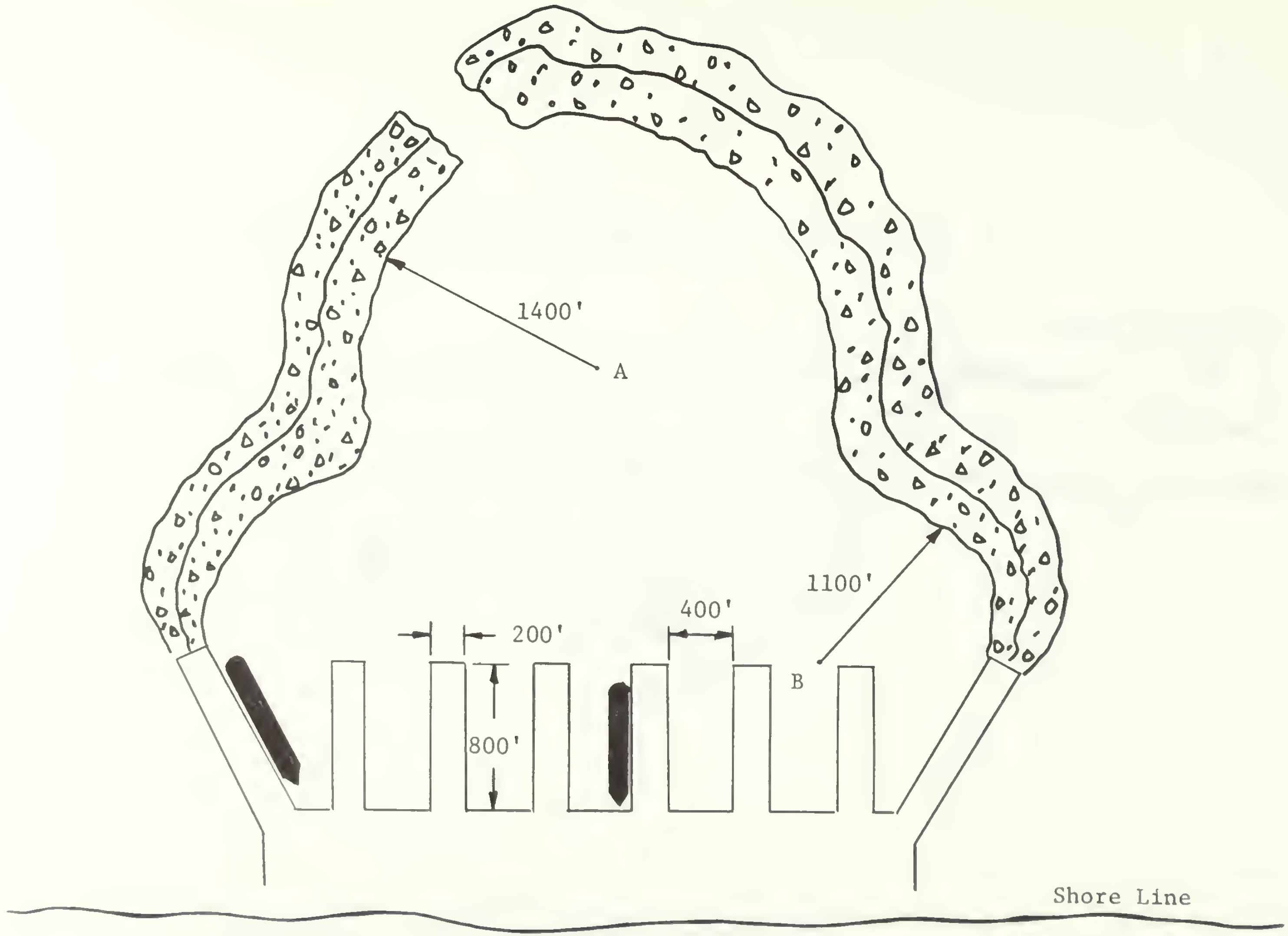


Figure IV.3 Nuclear Excavated Harbor (plan view)

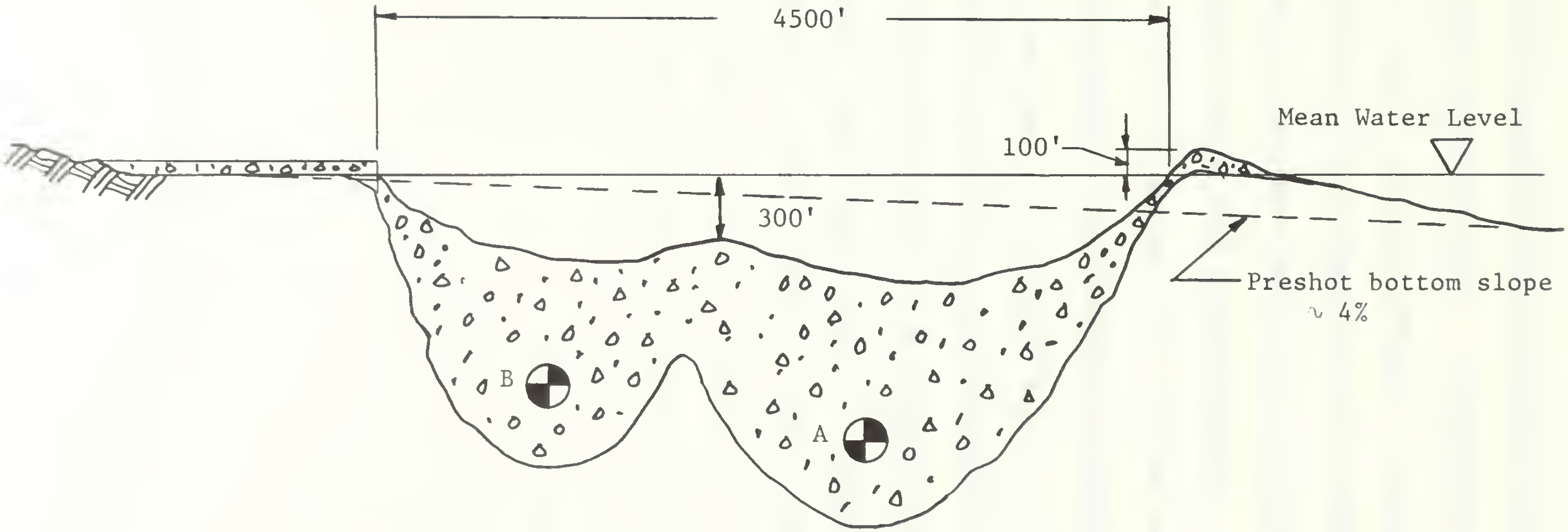


Figure IV.4 Nuclear Excavated Harbor (cross section)

The fallback slope on the inner side of the crater is similar to a talus slope, composed of broken material and concave upward, with the flattest portion near the base.[4] The angle of the steepest portion of the fallback slope is usually less than the angle of repose of the material. The material is thinnest where the slope is steepest. In effect, the head of the slope has little overburden and the toe of the slope is reinforced, which aids slope stability. The question of slope stability is one of the most important problems associated with the use of nuclear explosives for excavation purposes.

Present knowledge on the stability of crater slopes is somewhat meager.[9] However, data from the Sedan and Danny Boy investigations, together with theoretical studies and experiences with conventional excavations, permit some insight into this problem. The Sedan crater, which was excavated in desert alluvium, has an average slope of 38 degrees for the material above the fallback which includes the in-situ soils and ejecta forming the crater rim.[15] The average angle of internal friction of the in-situ soils is 43 degrees and ignoring the effects of cementation gives a factor of safety of 1.19 for relatively stable slopes. In assessing the stability of the Sedan slopes, the geology and environmental conditions of the area must be kept in mind if this data is to be used properly in estimating slope stability of excavations in other soil and climatic environments.

A massive rock with a random joint pattern has an angle of repose of about 70 degrees.[9] Consequently, rock slopes in nuclear craters may be stable at this angle; although if the rock is greatly fragmented, this angle may be as low as 45 degrees. The safe angle of repose of stratified rock may range between 30 and 90 degrees,

depending on the inclination of the bedding planes. No information is available yet on cratering in stratified materials in which the bedding planes are not parallel to the ground surface. However, in such cases stable slopes might be realized on one side of a harbor while unstable slopes would be present on the other.

In assessing the long-term slope stability of a nuclear excavated harbor, consideration must be given to the effects of wave action and ocean currents on the slopes. The effects of waves and ocean currents on seawalls and breakwaters is well documented and much of this technology can be used in determining the effects on crater slopes. Generally, a rubble mound breakwater consists of a large mass of stone so arranged that the smaller sizes form the lower central portion of the core and are protected by the larger stones forming the exterior slopes and upper portion, the latter being most severely exposed to direct wave action.[16]

The size of stone used and the breakwater slope depend on the water depth and the height of the waves. Roughly, the larger stones range from 4 to 27 tons with slopes of 1 on 1-1/4 to 1 on 3. The outer crater slope, which will be subjected to the most severe wave action, varies from 1 on 4 to 1 on 5. The ejected rock sizes on the outer crater slope in a hard rock medium will range up to 2 or 3 tons with 25 percent of the rock being greater than 1 ton.[17]

Initially there will be some errosions of the crater slopes as the smaller particles are dispersed and the larger rocks seek more stable positions. However, with time, the slopes should become stable and depending on the geologic medium and the characteristic wave

action of the area, additional rock could be placed on the slopes if required to ensure stability.

CHAPTER V

RADIOLOGICAL SAFETY ANALYSIS

A. Scope

This section discusses the nature, extent, and safety implications of the radioactivity produced by the subsurface detonation of nuclear explosives. A radiological safety analysis must be made for any proposed nuclear construction project to ensure that the radioactivity released to the environment does not reach man in amounts that will cause harmful effects.

This safety analysis is subdivided into three major areas of concern: on-site ground contamination of the crater and lip area, off-site ground contamination in the downwind fallout pattern due to passage of the radioactive cloud (local fallout), and on site water contamination due to tritium production in the thermonuclear explosion. Figure V.1 outlines the scope of a radiological safety analysis. For each of these three areas, a comparison will be made of the effects caused by each of the four different combinations of yield sizes described in Section IV.

This radiological safety analysis assumes that all charges are at a scaled depth of burst of 145 $ft/Kt^{1/3.4}$. The procedures followed throughout this section are based primarily on the methods developed by the U. S. Army Engineer Nuclear Cratering Group.[7] Included are the local fallout prediction and determination of the exclusion area and safe reentry times. The primary control measures to ensure public safety are: 1) evacuation of personnel from possible areas of contamination before the detonation and 2) monitoring

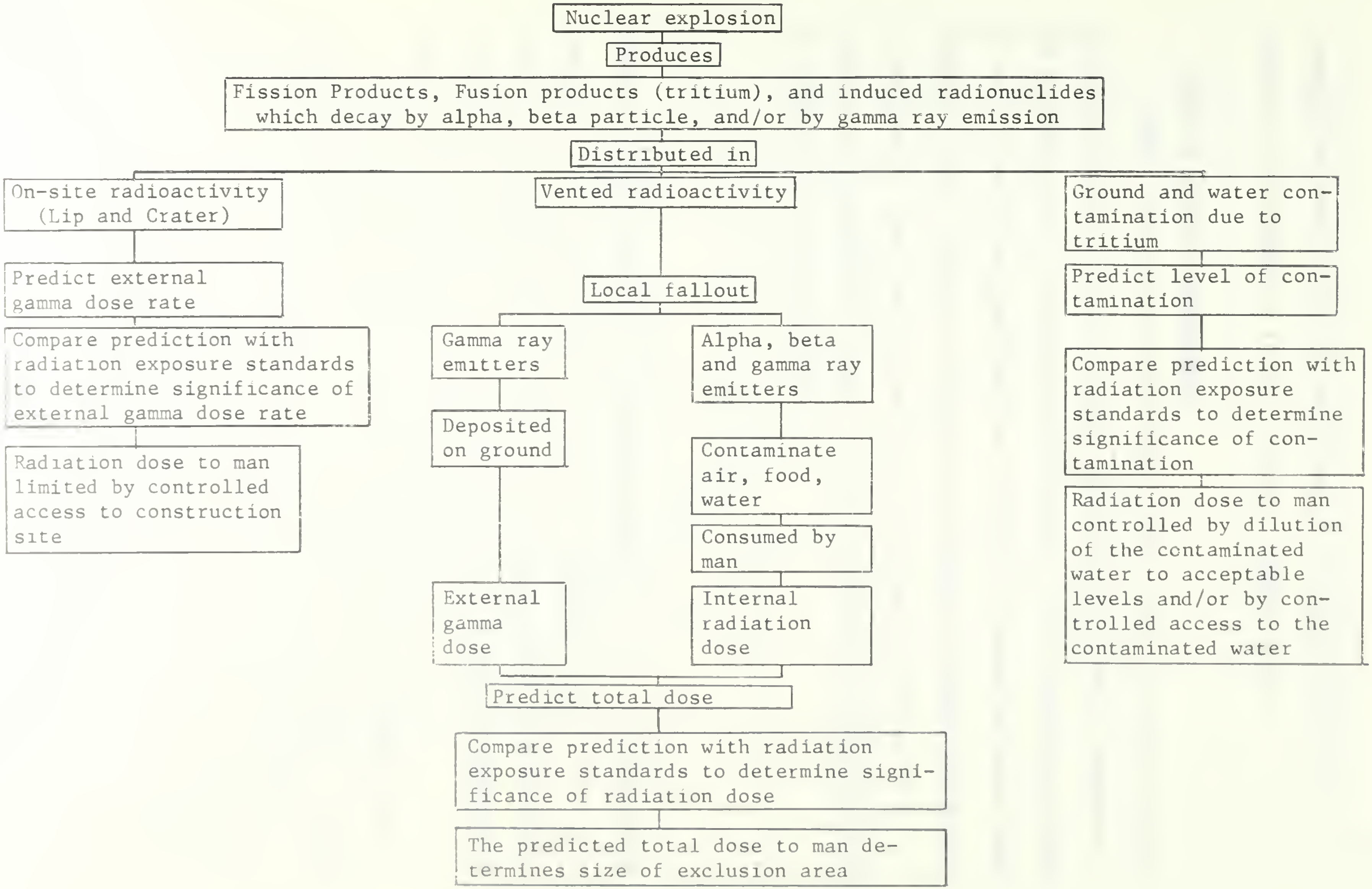


Figure V.1 Scope of Radiological Safety Analysis[7]

contaminated areas after the detonation to determine additional evacuation requirements, if any, and safe reentry times.

B. On-Site Ground Contamination

There are two sources of radioactivity from a nuclear explosion, the direct products of the nuclear reactions (the fission fragments and tritium) and the radioactivities induced in the surrounding medium by the explosion generated neutrons. Figure V.2 shows the significant fission product activities produced per kiloton of fission energy as a function of time after detonation. From these activities it is possible to determine the amount, N, of a particular radionuclide that is produced from the relation:

$$\frac{dN}{dt} = \lambda N$$

where $\lambda = \frac{0.693}{t_{1/2}}$ and $\frac{dN}{dt}$ is read from Figure V.2. For this radiation analysis, it is assumed that the fission trigger is equal to one percent of the total explosive yield but not greater than five kilotons total. The amounts of the longer lived fission products produced for four, 5 Kt fission devices are given in Table V.1

The induced radioactivities in the surrounding medium vary as do the elements which are naturally present in the medium. As with fission products, the induced radionuclides are neutron rich and undergo decay by beta particle emission with or without accompanying gamma rays. The significant isotopes that are produced by a nuclear explosion depend on the surrounding medium and in general are Ca^{45}, Fe^{55}, H^{3}, P^{32}, La^{140}, Na^{24}, Mn^{56}, and Al^{28}.

The external radiation dose is created by deposition on the

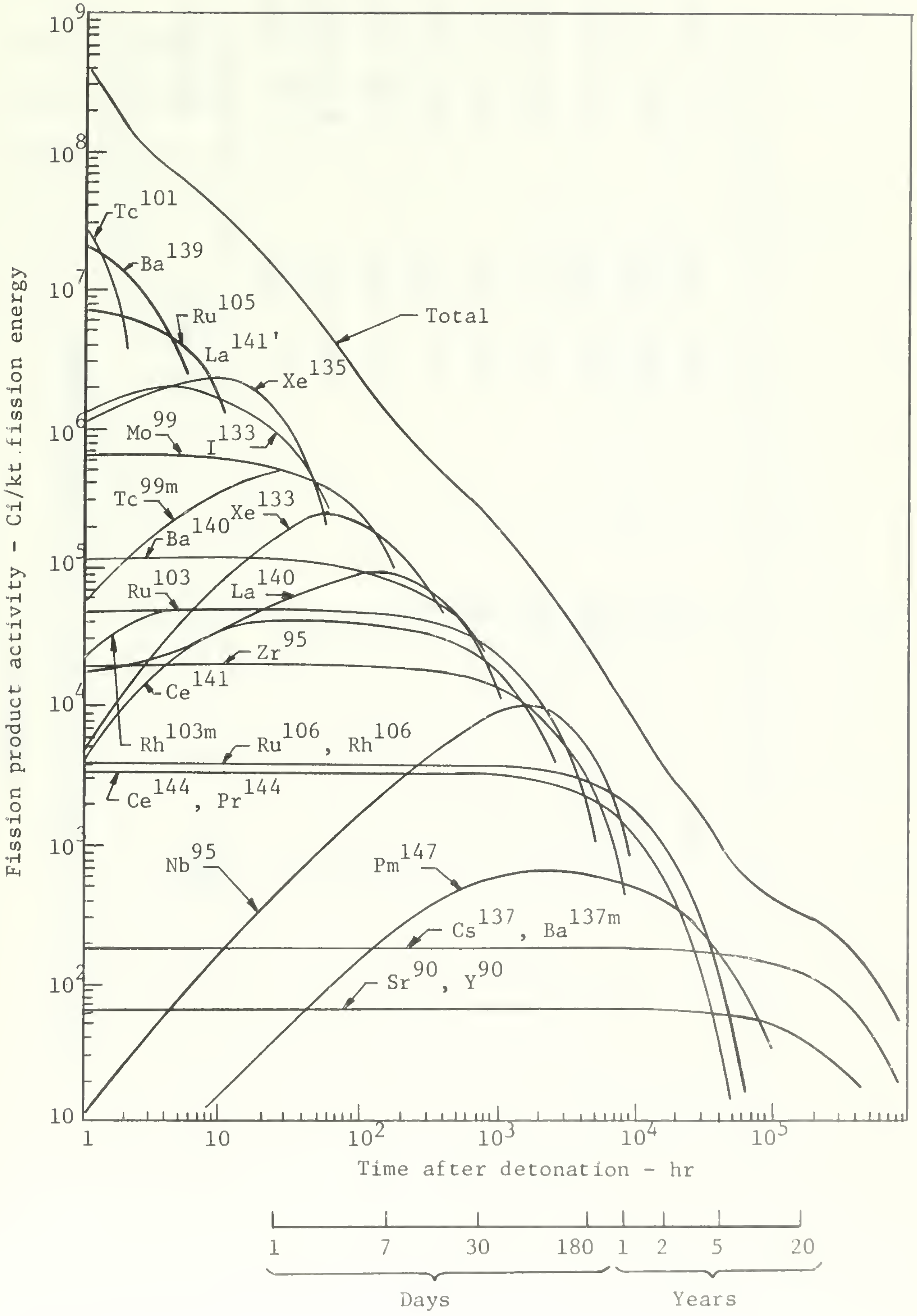


Figure V.2 Fission Product Activities

Table V.1

Fission Product Production for Four, 5 kt Fission Triggers

Nuclide	$t_{1/2}$(yr)	$\frac{t_{1/2}}{0.693}$	Ci/kt	$\frac{dN}{dt}\frac{(dis.)}{yr.}$	N(atoms)
Cs^{137}	33	47.6	190	4.42×10^{21}	2.09×10^{23}
Sr^{90}	28	40.4	67	1.56×10^{21}	6.29×10^{22}
Kr^{85}	11	15.9	13	3.03×10^{20}	4.81×10^{21}
Sb^{125}	2.7	3.9	22	5.12×10^{20}	2.00×10^{21}
Eu^{155}	1.7	2.46	120	2.80×10^{21}	6.87×10^{21}
Ru^{106}	1.0	1.44	5600	1.31×10^{23}	1.88×10^{23}
Ce^{144}	0.805	1.162	3400	7.92×10^{22}	9.22×10^{22}
Sn^{123}	0.364	0.525	200	4.66×10^{21}	2.45×10^{21}
Te^{127}	0.250	0.361	30	6.99×10^{20}	2.52×10^{20}

ground of gamma ray-emitting radionuclides that were produced by the nuclear detonation. This external dose rate will determine the safe reentry time for work in the crater and lip area. Figure B-1 (Appendix B) shows the H+1 hr external gamma dose as a function of yield. For the four cases considered, the H+1 hr doses are found to be

Case 1 (5 Mt)	γ (H+1) = 18.5 R/hr
Case 2 (3.5 Mt)	γ (H+1) = 24 R/hr
Case 3 (2.5 Mt)	γ (H+1) = 28 R/hr
Case 4 (1.1 Mt)	γ (H+1) = 49 R/hr

It is interesting to note that the largest yield produces the smallest H+1 hr gamma dose. This can be explained partially because the fission trigger was limited to a maximum of 5 Kt and as the total yeild increases the same quantity of radioactive material is dispersed over a wider area.

The next step is to determine the decay factor required to reduce the H+1 hr gamma dose rate to the acceptable limit of 2.5 mr/hr for a 40 hr work week. This decay factor is simply the acceptable limit divided by the H+1 hour dose above as follows:

Case			Decay Factor
1	$\frac{2.5 \times 10^{-3}}{18.5}$	=	1.35×10^{-4}
2	$\frac{2.5 \times 10^{-3}}{24}$	=	1.04×10^{-4}
3	$\frac{2.5 \times 10^{-3}}{28}$	=	0.893×10^{-4}
4	$\frac{2.5 \times 10^{-3}}{49}$	=	0.51×10^{-4}

The time required for this amount of decay to take place can be determined from the radioactive decay curve, Figure B-2. This time is then the safe reentry time for a 40-hour work week.

Case	Reentry Time (40 Hr. week)
1	2800 Hr ∿ 3.8 Mo.
2	3500 Hr ∿ 4.7 Mo.
3	4700 Hr ∿ 6.1 Mo.
4	6000 Hr ∿ 8 Mo.

The safe reentry time for the local population is based on limiting the first year external gamma dose to 0.17R. The external gamma dose conversion factor (EGDCF) required at time of reentry, T, to give an external gamma dose of 0.17 R is:[7]

$$EGDCF = \frac{\int_{T}^{1\ yr.} DR(t)dt}{DR_{H+1}} = \frac{0.17R}{DR_{H+1}(R/hr)}$$

and for the four cases is:

Case	DR_{H+1} (R/hr)	EGDCF
1	18.5	9.2×10^{-3}
2	24	7.08×10^{-3}
3	28	6.07×10^{-3}
4	49	3.47×10^{-3}

The time at which EGDCF(T) occurs is read directly from Figure B-3. The minimum time of reentry to the radiation fields with the H+1

hour external gamma dose rates determined above, for a first year resident to receive 0.17R are found to be:

Case	Safe Reentry Time (First Year)
1	5.3×10^3 Hr $\sim$ 7 Mo.
2	5.7×10^3 Hr $\sim$ 7.5 Mo.
3	6.3×10^3 Hr $\sim$ 8.5 Mo.
4	7.4×10^3 Hr $\sim$ 10 Mo.

Figure V.3 shows the comparison for each case of the safe reentry times for a 40 hour/week and the first year. It should be pointed out that radioactive decay was the only factor considered in developing Figures B-2 and B-3 for the estimated dose rate levels. The natural weathering processes, such as wind and rain, will result in a more rapid decrease in the external gamma dose rate and dose than those which are indicated. Also, the overlying body of water at surface ground zero may filter out some of the radioactive particles and, therefore, the reentry time estimates obtained above may be considered conservative.

C. Off-Site Ground Contamination

1. Cloud Formation

As stated before, the off-site ground contamination is caused by the release of radioactive materials in the downwind fallout pattern due to passage of the radioactive cloud. The radioactive cloud is formed from the explosion which projects earth particles, vaporized material, and explosive debris into the atmosphere. The larger particles fall back to the ground and entrap

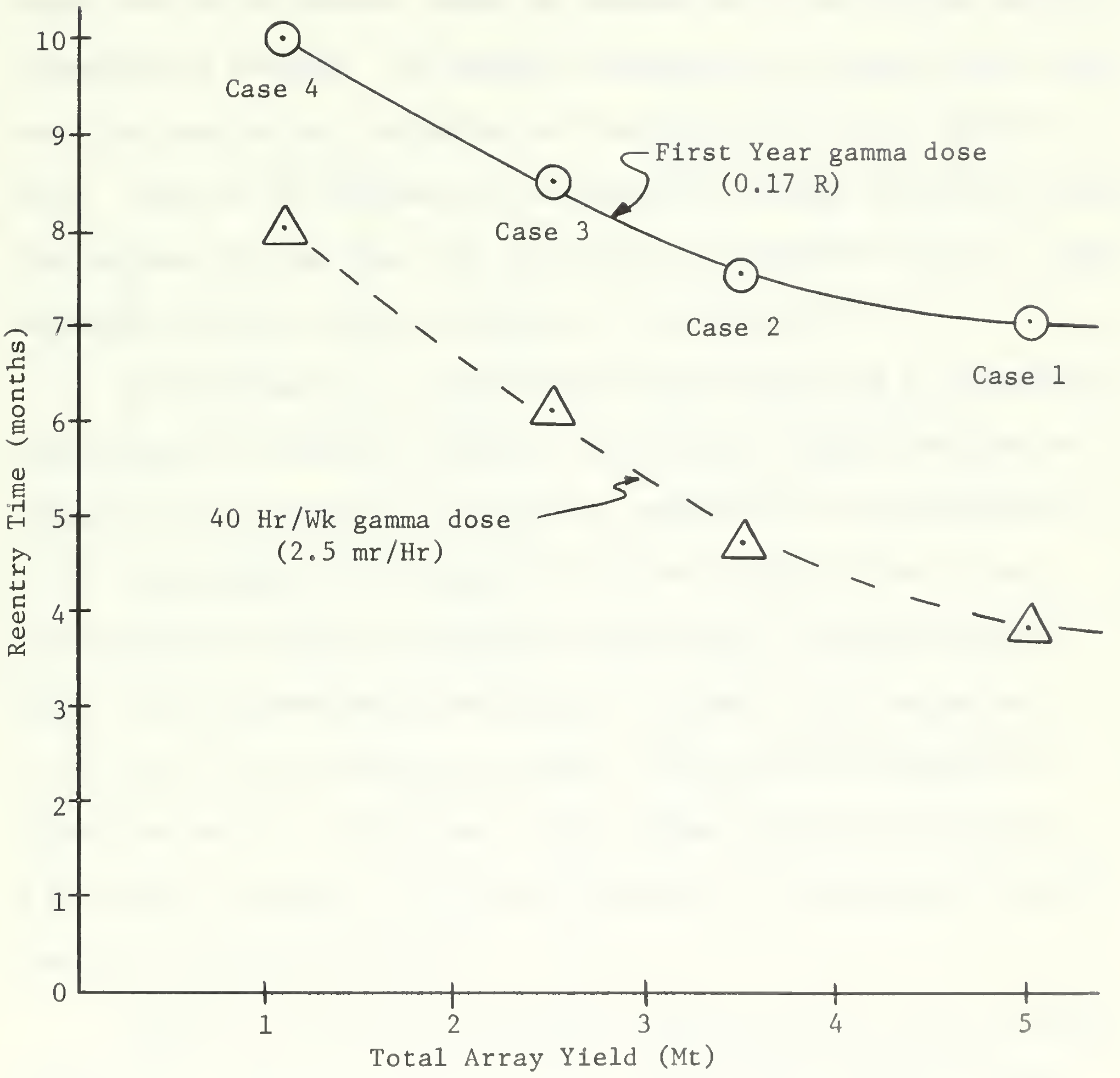


Figure V.3 Safe Reentry Time vs. Total Yield (Crater and Lip Area)

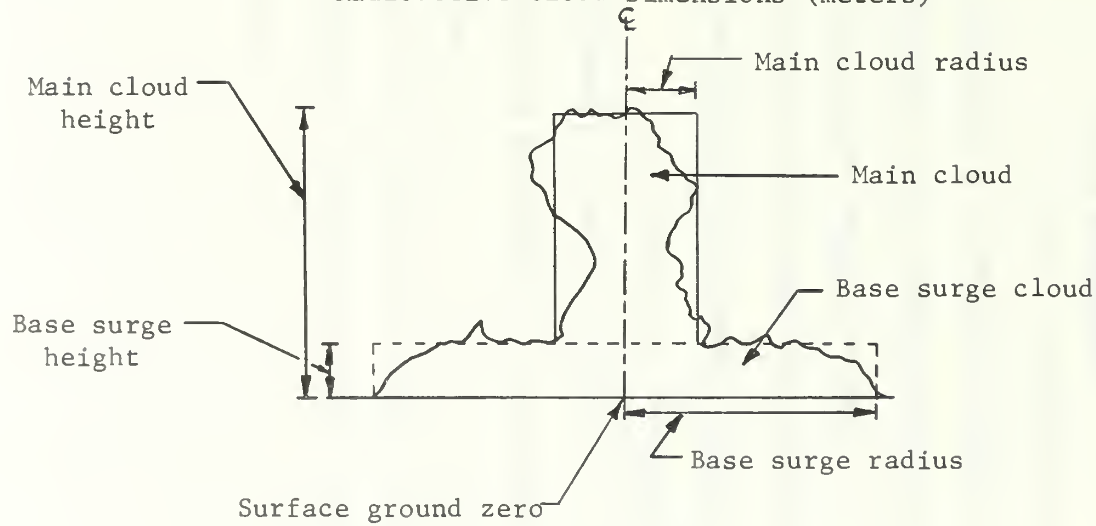
the finer dust particles and air.[4] This dust-laden air acts as a fluid and sweeps downward and outward from the base of the cylindrical column and is called the base surge. The main cloud, which contains the hot gases from the explosion, rises and expands until equilibrium with the atmosphere is reached. The escaped radioactivity is distributed downwind from the nuclear detonation as the particles of dust settle to earth. Some of the radioactive particles will remain airborne for such long periods of time that they contribute to worldwide fallout. This worldwide fallout is not considered in this analysis.

The phenomenon of cloud formation is complex and is affected by meteorological conditions, depth of burst, total yield, and type of material being excavated. It has been determined[7] that groupings of up to five charges will interact to produce a single cloud. The base surge cloud radius, base surge cloud height, and main cloud height may be determined from Figure B-4 using a yield equivalent to the sum of the yields for each case. The main cloud radius is determined using a yield equal to the largest charge in the group. A wet media is assumed. The cloud dimensions so determined for each case are given in Table V.2.

Figure B-5 gives the equivalent fission yield in the cloud and fallout as a function of total yield. The fission yield for each size nuclear explosive is first determined and then the total equivalent fission yield for each case is found.

Table V.2

Radioactive Cloud Dimensions (meters)



Case	Base Surge Radius	Base Surge Height	Main Cloud Radius	Main Cloud Height
1	1.7×10^4	3.0×10^3	3.5×10^3	7.5×10^3
2	1.6×10^4	2.9×10^3	3.5×10^3	7.0×10^3
3	1.4×10^4	2.7×10^3	2.6×10^3	6.7×10^3
4	1.2×10^4	2.2×10^3	1.8×10^3	5.8×10^3

Case	Total Equivalent Fission Yield (Tons)
1	178
2	151
3	141
4	114

2. Wind Hodograph

In order to determine the expected downwind dose levels, it is necessary to develop a wind vector diagram or Hodograph. The most probable wind conditions for the site area at the time of year of the proposed detonation must be obtained. The direction and speed of the winds from ground zero to the top of the cloud are the primary factors affecting the downwind fallout pattern.

The presence of an inversion may limit the cloud height and the presence of any precipitation could cause some of the radionuclides to be washed out of the cloud. This may result in more intense fallout or "Hot Spots" along the path of precipitation. These effects are variable and cannot be considered in a quantitative manner in making a radiological safety analysis. The best source of wind information is a local office of the weather bureau or a local airport. In all probability, an on-site wind analysis will have to be made for the most accurate prediction of downwind fallout. In addition, the terrain features of the area will have to be studied for possible effects of channeling on the fallout at lower levels.

To plot the Hodograph, the cloud is divided into layers, each of a certain thickness and representative wind vector. For illustration purposes only, the following hypothetical wind data will be assumed:

Altitude (m)	Layer No.	Layer Thickness (m)	Wind Speed (Knots)	Direction from which Wind is Blowing (Deg)
500	(1)	0-1000	10	180
1500	(2)	1000-2000	12	190
2500	(3)	2000-3000	12	200
3500	(4)	3000-4000	14	210
4500	(5)	4000-5000	14	220
5500	(6)	5000-6000	16	230
6500	(7)	6000-7000	18	240
7500	(8)	7000-8000	20	250

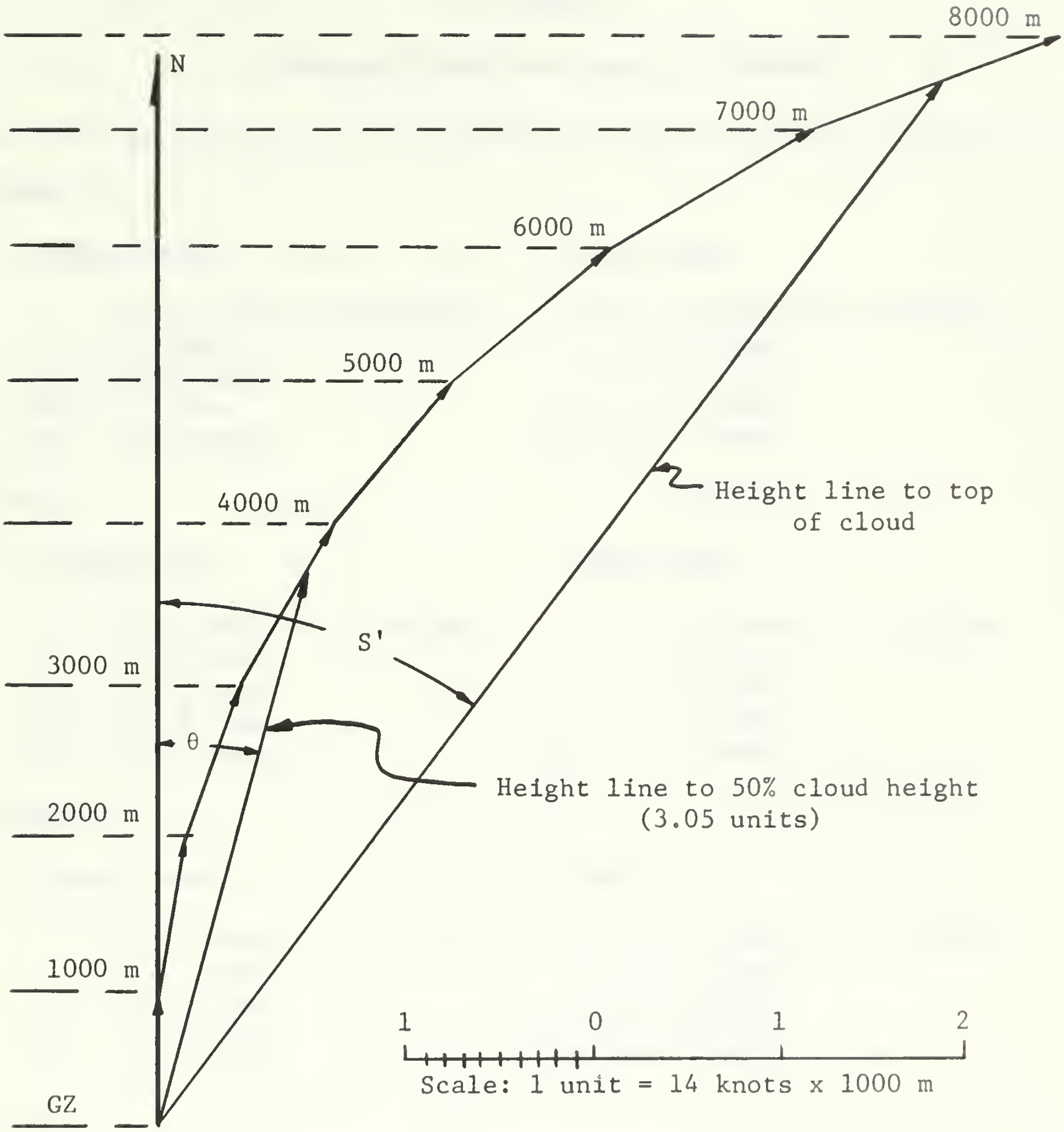
The wind vector length is a dimensionless quantity defined by

$$\text{wind vector length} = \frac{\text{wind speed of layer (knots) x layer thickness (m)}}{\text{P(knots) x Q(m)}}$$

where P and Q are arbitrary scaling factors used to provide a convenient technique for plotting the hodograph. The wind vector lengths are layed out end-to-end in the direction to which each wind is blowing. The resulting hodograph plot for Case 1, main cloud is shown in Figure V.4. Since both a main cloud and a base surge will be formed, a hodograph for both clouds must be made. The hodograph wind data for each case is given in Table V.3. The assumed wind data was chosen so as not to be unrealistic and winds in this range may reasonably occur.

3. Dose Level Predictions and Safe Reentry Times

Utilizing the data obtained from the hodograph, for the hypothetical case assumed, dose level predictions and corresponding



Effective wind velocity $\overline{V}' = \frac{3.05}{3750} \times 14 \times 1000 = 11.4$ knots = 13.1 MPH

Effective wind direction (θ) = 15 deg.

Effective wind shear (S') = 37.4 deg.

West shear = 15 deg. East shear = 22.4 deg.

Figure V.4 Wind Hodograph (case 1, main cloud)

Table V.3

Hodograph Wind Data (case 1 through 4)

Case 1:

Main cloud	Base surge
$\overline{V}'$ = 11.4 knots = 13.1 mph	$\overline{V}'$ = 10.8 knots = 12.4 mph
θ = 15 deg.	θ = 4.5 deg.
S' = 37.4 deg.	S' = 10.7 deg.
W.s. = 15 deg.	W.s. = 4.5 deg.
E.s. = 22.4 deg.	E.s. = 6.2 deg.

Case 2:

Main cloud	Base surge
$\overline{V}'$ = 11.6 knots = 13.34 mph	$\overline{V}'$ = 11.0 knots = 12.64 mph
θ = 13.8 deg.	θ = 4.2 deg.
S' = 33.2 deg.	S' = 10.2 deg.
W.s. = 13.8 deg.	W.s. = 4.5 deg.
E.s. = 19.4 deg.	E.s. = 6.0 deg.

Case 3:

Main cloud	Base surge
$\overline{V}'$ = 11.5 knots = 13.22 mph	$\overline{V}'$ = 10.4 knots = 11.95 mph
θ = 13.3 deg.	θ = 3.0 deg.
S' = 32.0 deg.	S' = 10.0 deg.
W.s. = 13.3 deg.	W.s. = 3.0 deg.
E.s. = 18.7 deg.	E.s. = 7.0 deg.

Case 4:

Main cloud	Base surge
$\overline{V}'$ = 11.4 knots = 13.1 mph	$\overline{V}'$ = 10.3 knots = 11.84 mph
θ = 11.0 deg.	θ = 1.3 deg.
S' = 26.5 deg.	S' = 7.0 deg.
W.s. = 11.0 deg.	W.s. = 1.3 deg.
E.s. = 15.5 deg.	E.s. = 5.7 deg.

safe reentry times can be predicted by the Weather Bureau scaling method. This method predicts the external gamma dose rate and the first-year dose along the "Hot Line" of the local fallout pattern. The "Hot Line" is defined as the line in the downwind direction along which the maximum external gamma dose rate occurs.

The basic dose rate prediction expression used in the Weather Bureau method is:

$$(DR)' = DR \left[\frac{\bar{v}}{\bar{v}'}\right]^2 \left[\frac{s}{s'}\right]^2 \left[\frac{(EFY)'}{EFY}\right]$$

$$x' = x \left[\frac{\bar{v}'}{\bar{v}}\right] \left[\frac{h'}{h}\right]$$

in which the unprimed quantities refer to a known reference case (Danny Boy Event in Basalt) and the primed quantities refer to values for the case to be predicted and,

DR = external gamma dose rate (R/hr)

$\bar{v}$ = effective wind velocity (knots)

s = wind shear (deg)

h = cloud height above the ground surface (m)

x = distance from SGZ (mi)

EFY = equivalent fission yield in the cloud and fallout

Figure B-6 gives the data from the Danny Boy Event required in the prediction method. It should be noted that this Weather Bureau scaling curve does not extend closer than about five miles to surface ground zero. In this region, deposition of fallout results from both normal fallout processes and the turbulent growth of the

base surge could along the ground. Consequently, predicting dose rates in this region is difficult. It is possible, however, to estimate the external gamma dose in this region by extrapolation between the predicted dose at the crater lip and the predicted dose at the point five miles from SGZ.

Since this proposed nuclear detonation will produce both a main cloud and a base surge cloud, a fallout calculation must be made for each cloud with the appropriate fraction of fission yield in each cloud. It is assumed that forty percent (40%) of the radioactivity is in the main cloud and sixty percent (60%) is in the base surge cloud.[7] The H+1 hour external gamma dose rates for each cloud are then summed at equal distances from the detonation point. The results of these calculations for each case are given in Table V.4.

The safe reentry time, in days, as a function of distance from surface ground zero for Case 1 are shown in Figure V.5. As previously stated, the curve is extrapolated between the safe reentry time to the crater lip area and the point five miles from SGZ. It should be noted that the variation in safe reentry times beyond five miles from SGZ for the four cases considered is very slight. The calculations indicate that the downwind extent of the exclusion area would be approximately sixty (60) miles. This is the distance at which the external gamma dose from cloud arrival to one year will be less than 0.17R. Doubling the wind speed for case one results in an extension of the exclusion area to approximately 75 miles.

Table V.4

H+1 hour External Gamma Dose Rates and Safe Reentry Times[a] vs. Distance from SGZ

Distance from SGZ(Mi)	H+1 Hr. γ-dose (R/hr)				Safe Reentry Time (Hr)			
	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
5	1.295	1.205	1.456	1.167	750	810	1200	1000
10	0.350	0.362	0.262	0.259	280	280	240	240
15	0.165	0.158	0.171	0.179	200	200	210	210
20	0.113	0.109	0.093	0.078	180	180	170	140
30	0.039	0.037	0.036	0.038	110	48	92	91
40	0.023	0.022	0.020	0.023	60	55	45	50
50	0.015	0.014	0.013	0.013	38	28	17	17
60	0.010	0.009	0.007	0.010	16	5	1	1

[a]Reentry time for first year gamma dose not to exceed 0.17R

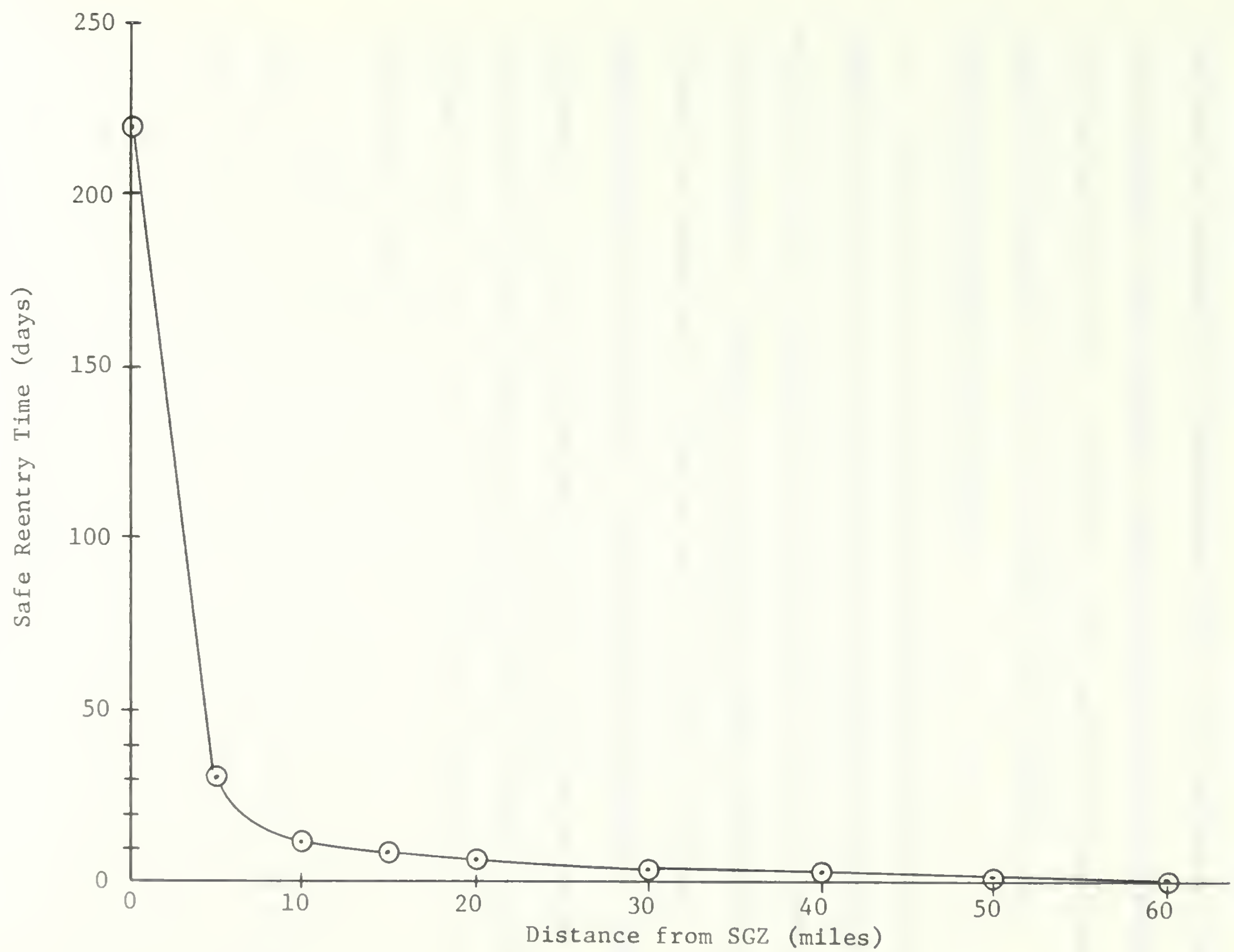


Figure V.5 Safe Reentry Time vs. Distance from SGZ, case 1

The results of this radiological safety analysis for off-site and on-site ground contamination allow comparisons to be made of the four cases considered. The ground contamination in the crater and lip area was greatest for the smallest total yield considered, whereas in the downwind fallout pattern, there was little or no difference in contamination levels. In addition to the relative cloud sizes for each case, comparison of the most probable wind directions and deviations (wind shear) can be made.

This analysis is not intended to provide any predictions of radioactive fallout for an actual nuclear detonation. The state of any portion of the atmosphere at any particular time may be known only imprecisely. Therefore, a radiological safety program based on forecasts of atmospheric variables needs to provide for large deviations from the forecasts. The Air Resources Laboratory of the Environmental Science Services Administration has done extensive work in the field of meteorology and nuclear detonation safety and has published some of the more recent developments in knowledge of air motion and in prediction techniques.[10]

Nuclear detonations are carefully timed to occur under weather conditions that meet safety requirements or under conditions within which emergency measures can be taken to ensure human safety. All detonations can be cancelled or postponed by the project manager up to within a few minutes of the detonation time so that late changes in weather can be analyzed.

D. On-Site Tritium Concentrations

Tritium, one of the major by-products of the fusion reaction,

has a half-life of 12.3 years and emits a comparatively low energy beta particle (18 Kev). Tritium may be significant to the internal radiation dose because it occurs mainly as tritiated water (HTO) which is chemically indistinguishable from ordinary water (H_2O). Ground and surface water in the locality of the detonation, therefore, may become contaminated with tritium to such an extent that a safety hazard may exist.

In a nuclear harbor excavation, a large body of tritium contaminated water will be formed that may initially be isolated from the surrounding sea by the crater lip. It is the purpose of this section to estimate the amount of tritium that could be expected in this contained volume for each case under consideration. An unclassified estimate indicates that approximately 20 kCi of tritium will be released per kiloton of total yield.[7] It is assumed that 50 percent of the tritium produced will be trapped in the crater and fallback material. It is further assumed that the crater formed will rapidly refill with sea water with the tritium being equally distributed throughout the fallback material and water inside the crater volume. Estimating the crater volume (including fallback) for each case, the tritium concentrations based on the above assumptions are given in Table V.5.

The maximum permissible concentration (MPC) of tritium in water to be consumed by the general public is 0.001 $\mu Ci/cm^3$. The calculations here indicate that the tritium concentration could be as high as 100 times the allowable MPC for drinking water. This is not to say that the water in the crater should be suitable for human consumption, but rather to indicate the level of tritium present that

Table V.5

Tritium Concentrations in Crater and Fallback Material ($\mu Ci/cm^3$)

Case 1	0.116
Case 2	0.105
Case 3	0.116
Case 4	0.101

may enter man's food chain indirectly by his consumption of animals and plants exposed to the contaminated water. Controlled release of this contaminated water to the surrounding sea may have to be considered in order to ensure that there is no safety hazard to the marine life in the area. In addition to the possible marine hazard, tritium may also be deposited on the surrounding vegetation. Before a complete radiological safety analysis can be made, the relationship between man and his environment, which involves naturally occurring ecological concentrations and dillution processes, must be known as well as the quantity of each radionuclide produced and its contribution to the radiation dose. The ecological processes are difficult to estimate since they depend on the time of year, the local climate, vegetation, agricultural methods, and the dietary habits of both man and animals living in the contaminated areas. Such a study is beyond the scope of this analysis but the reader is referred to a similar study conducted by the AEC for a proposed nuclear harbor in Alaska[11] and other Bio-ecological studies based on many of the Plowshare tests at the Nevada Test Site.[12,13]

CHAPTER VI

SEISMIC AND AIR BLAST EFFECTS

A. Ground Shock Considerations

Almost all the constructive applications of nuclear explosions depend on the tremendous pressures developed, pressures so high that rock and earth behave like fluids. Part of the energy of the explosion is propagated through the earth as seismic waves. Far from the source these waves are simple sound waves, having degenerated from very strong shock waves. For a large yield explosion, damage due to earth motion from these waves can be very extensive near the point of detonation. Because the destructive power of these waves decreases with distance, it is possible to estimate zones and type of damage expected from an explosion.[4,18] In estimating the possible extent of damage, consideration must be given to several factors such as, type of medium in which the blast takes place and where structures are located, the type of structures whether engineered or residential and the distances from the explosion point.

The primary basis for ground shock predictions is the large amount of empirical data which has been collected as a part of the AEC's nuclear testing program at the Nevada Test Site. The applicability of the NTS information to other geographical areas has been verified by several nuclear events which have been detonated at locations other than NTS.[7] The nature of the medium in which the device is detonated will affect the fraction of explosive energy which is coupled into the medium and radiated as seismic Detonations in stong, competent rocks, such as basalt or granite, are

more efficient seismic sources than those in weaker and more compressible media, such as alluvium and tuff. There are indications that a cratering explosion will couple less seismic energy into a medium than a fully contained explosion. The difference may be as high as a factor of 2, however, this is not sufficiently documented to warrant it being taken into account in predicting ground motion.

For this analysis, the detonation medium will be assumed as competent rock (basalt, granite) and the medium at the point of interest is assumed as hardrock. The equation for predicting peak amplitudes of ground motion is then

$$A = \frac{500\ W^{0.70}}{R^2}\ \text{cm/sec}^2$$

where A is the ground acceleration, W is the yield in kilotons and R is the distance from SGZ in kilometers. An absolute threshold of damage cannot be defined as the severity of ground shock-induced damage to any structure will depend as much on the type and condition of the building as on the level of ground motion to which it is subjected. The approximate threshold of perception (which varies with individuals) is an acceleration of 1 cm/sec^2. An acceleration of 16 cm/sec^2 is generally an accepted level for minor architectural damage to residential structures. Between 16 cm/sec^2 and 100 cm/sec^2 there is a possibility of actual damage occurring. The percentage of damage to a structure is assumed to vary from 5 percent of its value for an acceleartion of 100 cm/sec^2 to 100 percent at 2000 cm/sec^2. Table VI.1 lists the predicted distance from SGZ corresponding to these acceleration levels for the four cases of yield sizes.

Table VI.1

Distance(Mi) vs. Ground Acceleration Levels(cm/sec^2)

	A = 1	A = 16	A = 100
Case 1 (5 Mt)	R = 274	R = 68.5	R = 27.4
Case 2 (3.5 Mt)	R = 240	R = 60.3	R = 24
Case 3 (2.5 Mt)	R = 215	R = 53.9	R = 21.5
Case 4 (1.1 Mt)	R = 158	R = 39.6	R = 15.8

Based on the location of these three zones of motion and an account of the number and types of buildings located in each zone, it is possible to develop cost estimates for expected damage.[14] These calculations indicate that care should be taken in selecting a proposed harbor site to allow a 15 to 30 mile radius within which there are very few structures.

B. Airblast Considerations

In addition to the seismic waves, there is associated with any explosive excavation project, nuclear or conventional, the possible hazard of blast waves. There is no difference between the blast waves produced by the two types of explosions, only the larger the explosion the farther its effects are felt.

Relatively weak blast waves can alarm people even if no serious damage is done. The damage caused from the blast wave of a nuclear explosion can be very extensive and is dependent on a number of factors. Generally speaking, sound propagation through the atmosphere is not uniform. Numerous tests have been conducted and measurements

made to predict theories of blast wave phenomena. The predictions made possible by this experience are somewhat uncertain, owing to factors similar to those encountered in weather forecasts.[4]

The motion of the earth above the explosion generates the air blast wave. The three major contributions to the air-blast are the spall, gas acceleration, and massive gas venting. Wind, temperature, and atmospheric pressure all play an important role in the propagation of an air blast. In addition, the air blast can be refracted off the atmosphere and focused back to earth. This can produce a region of increased intensity of the wave. The jetstream winds can also affect the distribution of the blast wave which could result in damage 150 miles away from the explosion.

The dominant airblast source mechanism (ground shock or gas vent) follows the same trend as the dominant mechanism in the cratering process and is peculiar to the geologic medium in which the nuclear detonation occurs. For nuclear detonations in hard, dry rock up to a yield of 5 kt, the ground shock-induced pulse has been dominant. For nuclear detonations in alluvium up to a yield of 100 kt, the gas-vent-induced pulse has been dominant. Pertinent experience does not exist at this time for other media.[7] The airblast overpressures predicted in this section are found by scaling from a standard overpressure-range curve for a one kt free air burst detonated in a standard atmosphere with a zero sound velocity gradient. Only the dominant wave is considered, with no specific indication as to whether it is the ground shock-induced or the gas vent-induced portion of the wave. This curve is shown in Figure C-1. Also included in this figure are the scaling relationships used to predict the

overpressures for other yields.

Since the scaling curve is based on a free air burst, a transmission factor (TF) must be used to relate the overpressures for a subsurface detonation.

$$TF = \frac{\text{Subsurface Burst Overpressure}}{\text{Free Air Burst Overpressure}}$$

Figure VI.1 is a plot of the transmission factor as a function of scaled depth of burst in the region of general interest for nuclear construction applications. The scaled depth of burst for Cases 1 through 4 is approximately 110 ft/kt$^{1/3}$ which corresponds to a TF = 0.27.

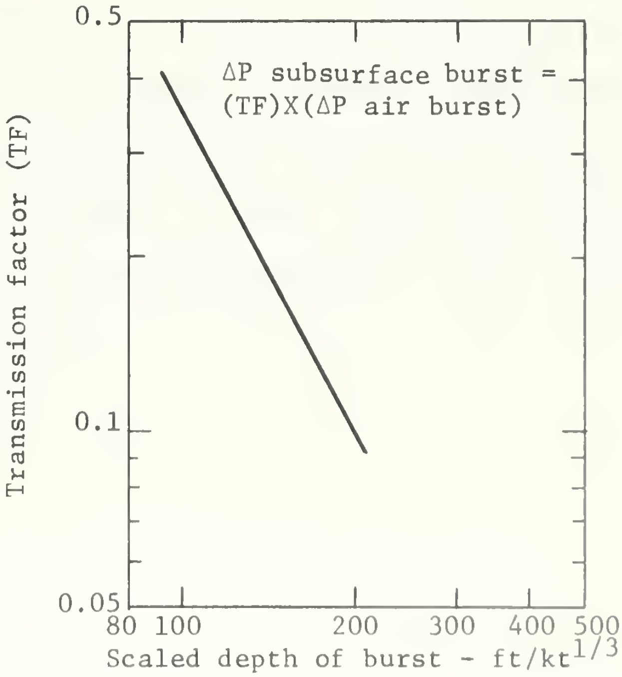


Figure VI.1 Transmission factor as a function of Scaled Depth of Burst[7]

A single average yield size is used for each case to predict airblast overpressures and the resulting amplitudes are multiplied by $N^{0.7}$ where N = number of charges in the array. The resulting overpressures for Case 1 through 4 are shown in Figure VI.2. The possible extent of structural damage for various overpressures are also indicated in the figure. Adjustments must be made to these predicted overpressures for those expected for specific meteorological conditions. Table VI.2 lists some of the amplitude and reduction factors for various atmospheric conditions.

Comparing these results and those of the predicted ground shock-induced damage it appears that the damage resulting from ground motion will overshadow the airblast effects. Damage resulting from seismic and blast waves can be minimized by selecting the proper site for an explosion (not too close to populated areas) and taking advantage of wind direction, time of year and other factors. By taking advantage of the most favorable conditions, nuclear explosive excavations can be carried out safely with no undue risk to the health and safety of the public.

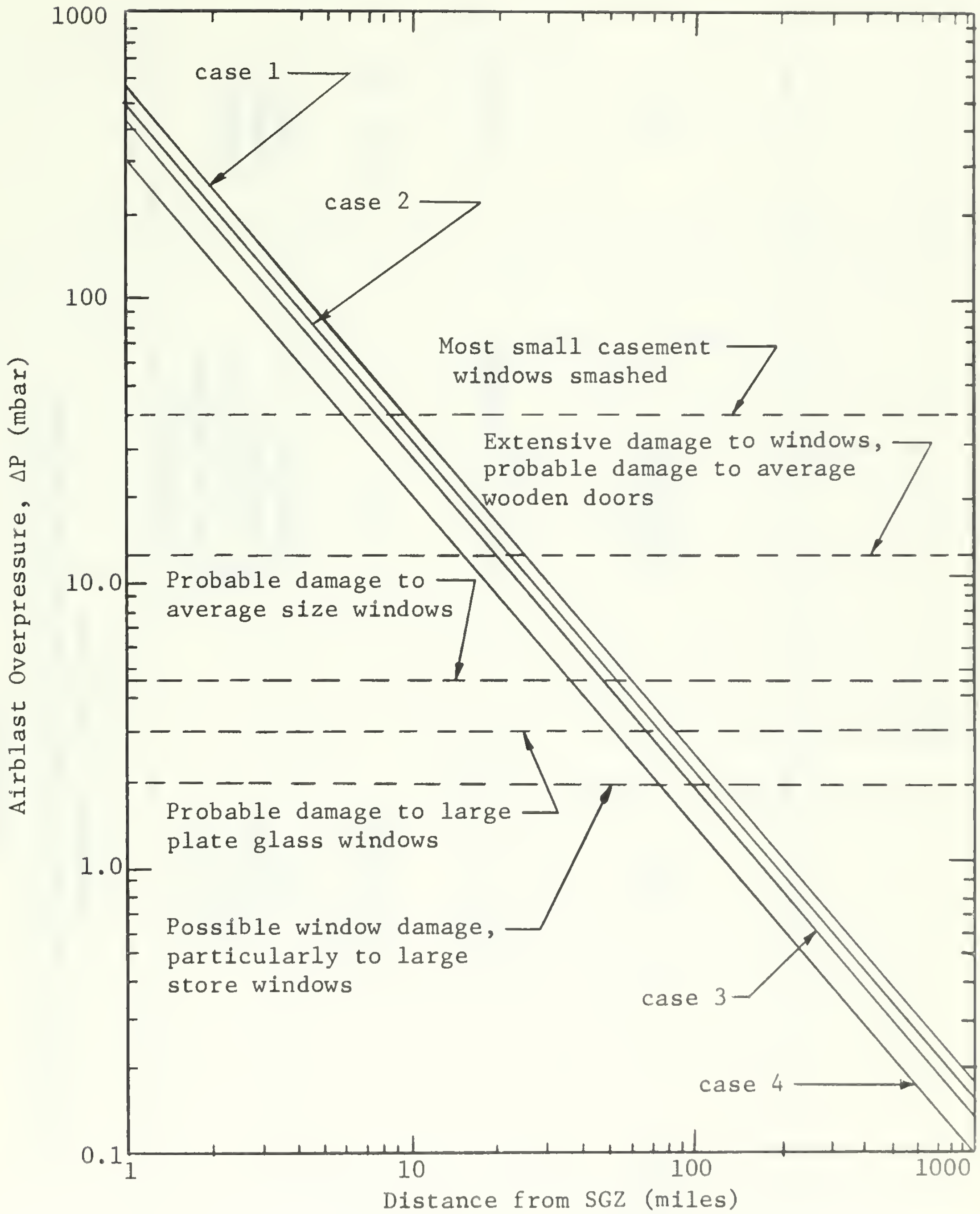


Figure VI.2 Airblast Overpressure vs. Distance from SGZ for Cases 1 through 4

Table VI.2

Overpressure Amplitude Correction Factors for Various Atmospheric Conditions

Causative atmospheric condition	Altitude interval of interest (ft)	Correction factor as applied to standard predicted overpressure	Range interval (mi)
Atmospheric temperature inversion of downwind	Surface to few thousand	2-3	up to 30
Jet steam winds in troposphere	25,000 to 18,000	up to 15 (average 3 - 4)	30 to 100
Upwind direction and/or decrease in air temperature with altitude	all	1/10 ($\Delta P \propto R^{-2}$)	100

CHAPTER VII

COST ANALYSIS

The economic advantage that the use of nuclear explosives may offer over conventional methods of harbor construction is dependent on a variety of considerations. It is very difficult to apply a dollar for dollar comparison to these two techniques of harbor construction because of the many different aspects of each type of construction and the possibility that one method may favor a different geological siting. To illustrate this, consider the excavation of one very large hole, say 100 feet deep and 400 feet in diameter, constructed in hard rock. Using conventional methods of excavation may require a combination of explosives, machinery and many man-hours of labor to accomplish the project. By contrast, it may well be possible to simply drill a hole and place one nuclear charge that will excavate the required size hole, at considerable savings in time and expense. At a different site, where the medium is a loosely compacted silty material, the excavation may be accomplished with earth moving equipment, or dredges if underwater, without the aid of explosives either conventional or nuclear.

Should a project require a large quantity of explosives, then the explosive costs themselves may influence the economic considerations. The cost of conventional explosives is approximately $460/ton for TNT and $120/ton for ANFL, while the cost of nuclear explosives ranges from $35/ton for a 10 kt yield to $0.30/ton for a 2 Mt yield.[4] There is, however, a lower limit on the size of nuclear explosives available

Table VII.1

Nuclear Emplacement and Yield Costs[7]

Rotary Drilling Costs				
Yield Size (Kt)	200	500	1,000	2,000
D.O.B. (ft.)	690	900	1,100	1,350
Canister Dia. (in.)	34	45	45	45
Casing Dia. (in.)	42	54	54	54
Hole Dia. (in.)	72	84	84	84
Drill Rig Size (HP)	1,000	1,375	1,375	1,375
Set up and Tear down cost ($ Lump Sum)	93,000	111,000	111,000	111,000
Drilling Cost ($/ft of hole)	127	196	196	196
Casing and Cementing costs ($/ft of hole)	181	297	297	297
Total emplacemnt Cost ($)	306,000	555,000	555,000	555,000
Nuclear Yield Cost ($)	490,000	530,000	550,000	600,000
Total Cost($)	796,000	1,085,000	1,105,000	1,155,000

from the AEC. This cost comparison indicates that there is a trade off point beyond which only nuclear explosives are economical and that for small projects economics will continue to dictate the use of conventional explosives.

Included in the cost of a nuclear excavation project are the costs associated with drilling and casing of the holes for emplacing of the nuclear explosives. Table VII.1 lists the itemized emplacement and yield costs for the four yield sizes used in this analysis. Table VII.2 lists the total cost associated with each of the four cases considered.

Table VII.2

Total Emplacement and Yield Costs for Cases 1 Through 4

Case 1	(5 Mt)	4.47 Million Dollars
Case 2	(3.5 Mt)	4.41 " "
Case 3	(2.5 Mt)	4.36 " "
Case 4	(1.1 Mt)	3.47 " "

Another important advantage of nuclear explosions that would reduce the cost of operations is that of compactness. For example, a nuclear charge of a few kilotons would weigh a few thousand pounds and could be placed down a 30-inch diameter hole, while a chemical explosive of the same energy release would weigh a few thousand tons and would occupy a volume of several thousand cubic meters.[4] Considerable savings in the cost of transporting and emplacing the

explosive would then be realized with nuclear explosives. The cost savings of still larger explosives is even more dramatic. As stated before, a dollar for dollar cost comparison is difficult and only the most efficient conventional method of constructing a specific project should be compared to the cost of utilizing nuclear explosives.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

The use of nuclear explosives for large scale excavation projects will depend primarily on the location of the proposed project site. To ensure that there will be no undue risk to the health and safety of the public and also to prevent any harmful effects on the environment, the safety implications of radioactivity and ground shock will have to be accurately predicted. These predictions are required in order to minimize and control any possible dangers. For this proposed project, a site would have to be selected in a remote area where there is little or no population or structures for a distance of 15 to 30 miles from the site. It should be pointed out that a harbor tends to speed the growth of an area.[4] Projects such as this in a remote area would have an accelerating economic return as the surrounding region developed.

It was shown that from one to five megatons of nuclear explosives will create an excavation in hard rock suitable for a medium size harbor for approximately 12 to 14 large ocean going freighters. The cloud height for a 5 Mt total yield will rise to 7500 meters (approximately 4.5 miles) for the assumed wind data (10 to 20 knots), radioactivity can be spread over a distance of up to 60 miles from the detonation point. To ensure adequate safety precautions for the public, evacuation will be required from the contaminated areas ranging from 7.5 months at the crater area to one day at a distance 60 miles downwind. It was also determined that for the smaller 1-Mt total yield, the radiation intensity was greatly

increased in the crater and lip area, and requires evacuation for 10 months.

The radiation intensities and fallout pattern are dependent on the actual meteorological conditions prevailing at the time of detonation. The wind data that was assumed in this analysis was chosen so as not to be unrealistic. In actuality, winds could reasonably be expected to prevail that would result in radioactive fallout less than or equal to that predicted in this analysis. No attempt was made in this analysis to relate the assumed wind conditions to a specific location or region of the world. Determination of actual on-site atmospheric conditions requires detailed and exhaustive investigations that are beyond the scope of this paper.

The tritium concentrations in the crater and lip area were determined to be 2 orders of magnitude above the allowable MPC for drinking water. These concentrations will demand careful monitoring of the surrounding vegetation, ground water, and sea life to ensure there is no risk of unacceptable levels of tritium reaching man through his food chain.

Ground shock disturbances for the 5-Mt total yield case will cause extensive damage to, or total destruction of, buildings within a radius of 27 miles. Broken windows can be expected within approximately 70 miles. The threshold of perception may range as far as 300 miles depending on the individual and the geologic medium. From the results of the predicted airblast damage, it appears that the damage caused by ground motion will be most severe.

The cost of the nuclear explosives and drilling of emplacement holes for the four cases considered ranged from 3.5 to 4.5 million dollars. No attempt was made to determine the possible savings in time and/or equipment costs that nuclear excavation may offer over conventional construction techniques. There also exists additional costs for environmental investigations and implementation of safety programs required with the use of nuclear explosives that were not considered.

In conclusion, it is apparent that nuclear explosives exhibit an exceptionally efficient method for creating large artificial harbors in many areas of the world with no undue risk to the health and safety of the public. In addition, the use of nuclear explosives will have many economical advantages over conventional excavation methods.

BIBLIOGRAPHY

1. "Peaceful Uses of Nuclear Explosives," Nuclear News, Volume 11: No. 3, March 1968.

2. Hughes, Bernard C., "The Corps of Engineers Nuclear Explosives Studies for Civil Construction," U.S. Army Engineer Nuclear Cratering Group, Lawrence Radiation Laboratory, Tech RPT 8, October 1968.

3. Quinn, Alonzo, DeF., Design and Construction of Ports and Marine Structures, McGraw-Hill, Inc., New York, 1961.

4. Teller, Edward, et al., The Constructive Uses of Nuclear Explosives, McGraw-Hill, Inc., New York, 1968.

5. Lombard, David B., "Plowshare," Physics Today, Volume 14, October 1961.

6. Johnson, Gerald W., "Excavation with Nuclear Explosives: Promise and Problems," Physics Today, Volume 16, November 1963.

7. Hughes, Bernard C., "Nuclear Construction Engineering Technology," U. S. Army Engineer Nuclear Cratering Group, Lawrence Radiation Laboratory, Technical Report No. 2, September 1968.

8. Ginsburg, T., "The Peaceful Uses of Nuclear Bombs in Civil Engineering," UCRL-Trans-717(L), June 1961.

9. "Engineering with Nuclear Explosives," Proceedings of the Third Plowshare Symposium, TID-7695, April 1964.

10. "Technical Discussions of Off-site Safety Programs for Underground Nuclear Detonations," United States Atomic Energy Commission, Nevada Operations Office, NVO-40, May 1969.

11. Wolfe, John N., "Bioenvironmental Features of the Ogotoruk Creek Area, Cape Thompson, Alaska," Report of Committee on Environmental Studies for Project Charriot, TID-17226, October 1962.

12. Harrison, Florence L., "Radioactive Debris from Underground Nuclear Explosions: 1. Physical and Chemical Characteristics, 2 Biological Availability of the Radionuclides to Aquatic Animals," Lawrence Radiation Laboratory, UCRL-50596, February 1969.

13. Rhoads, William A., Et al., "Ecological and Environmental Effects from Local Fallout from Cabriolet," PNE-956, June 1969.

14. Nadolski, M. E., "Architectural Damage to Residential Structures from Seismic Disturbances," Lawrence Radiation Laboratory, UCRL-71015, April 1968.

15. Strohm, W. E., Et al., "Stability of Crater Slopes-Project Sedan," U. S. Army Engineers Waterways Experiment Station, PNE 234 F, October 1964.

16. Proceedings of First Conference on Coastal Engineering, Council on Wave Research, The Engineering Foundation, October 1950.

17. Hansen, Spenst M., and Toman, John," Aggregate Production with Nuclear Explosives," Lawrence Radiation Laboratory, UCRL-12180 Rev. 2, May 1965.

18. Glasstone, Samuel, The Effects of Nuclear Weapons, U. S. Atomic Energy Commission, Washington, D. C., February 1964.

APPENDIX A

Figures A-1 and A-2[7] are curves (based on the empirical $W^{1/3.4}$ scaling law) which may be used to predict apparent crater dimensions (R_a and D_a) as a function of depth of burst (DOB) for hard, dry rock, and wet, weak clay shale. These curves summarize both high-explosive and nuclear-cratering detonations to date.

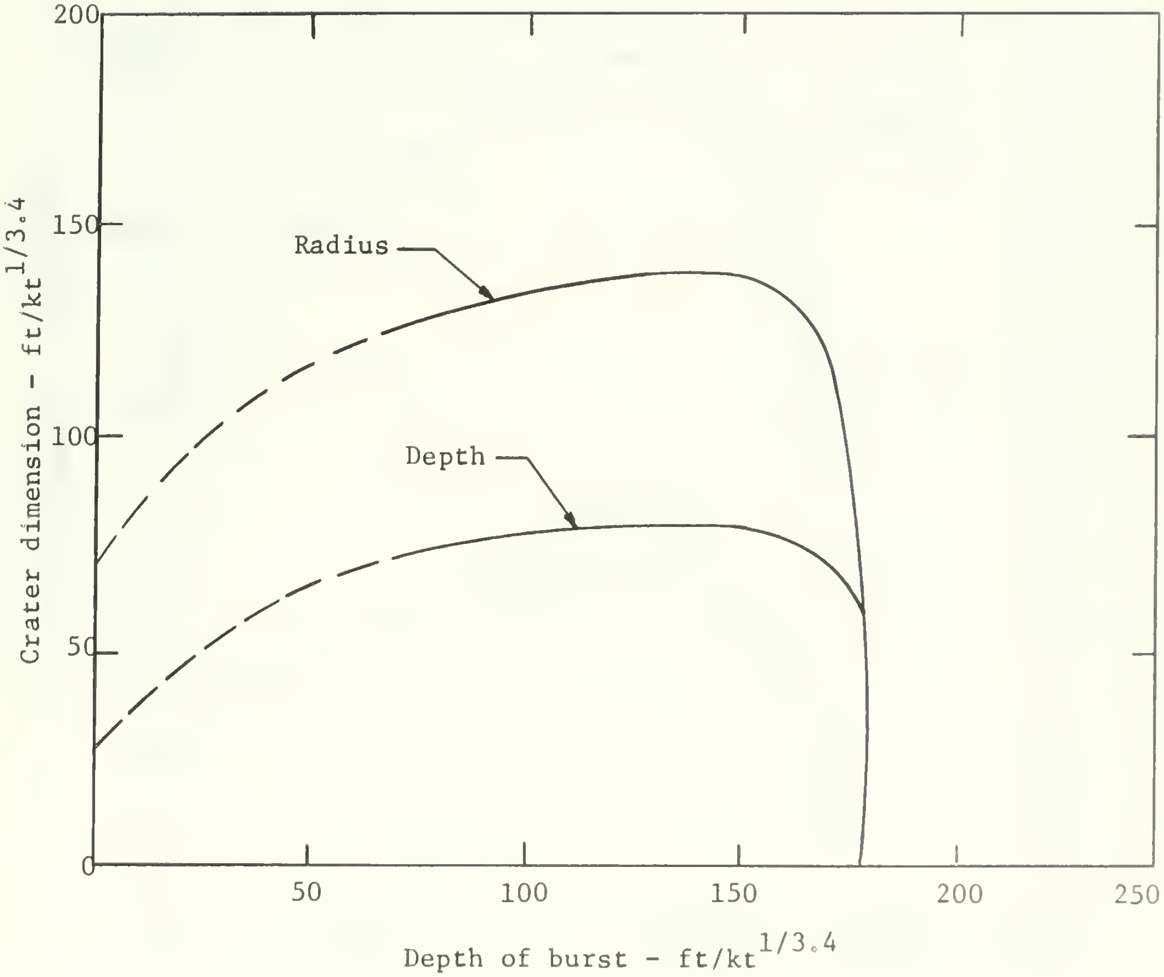


Figure A-1 Apparent Crater Dimensions vs. Depth of Burst for Hard, Dry Rock

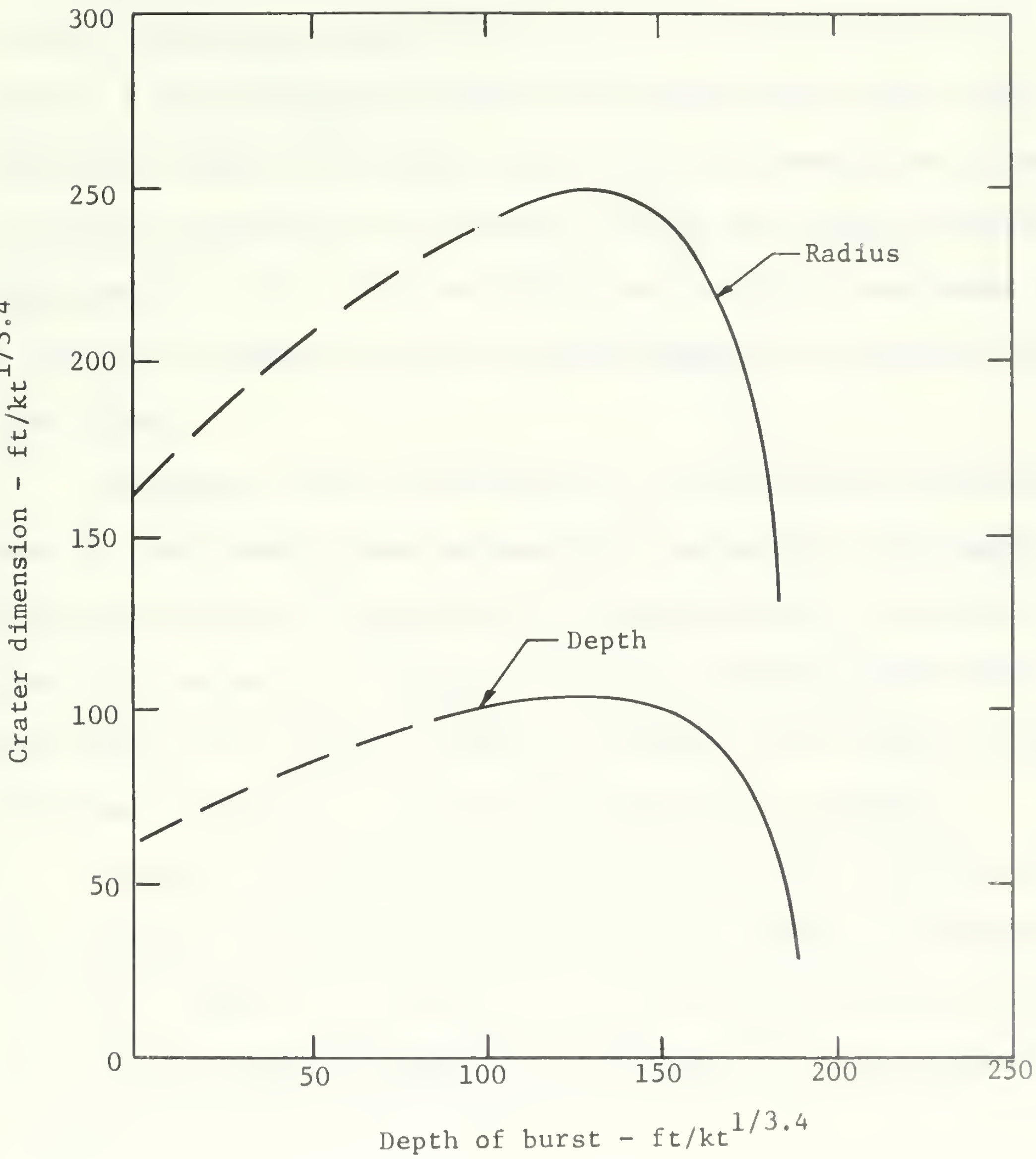


Figure A-2 Apparent Crater Dimensions vs. Depth of Burst for Wet, Weak Clay Shale

APPENDIX B

Figure B-1[7] is a plot of the external gamma dose rate at H+1 hr. in the crater and lip area as a function scaled DOB and yield. In developing this curve, it was assumed that only a few kilotons of energy from a high yield device will result from fission. It was also assumed that the fission products and induced radionuclides which are not in the cloud and fallout are uniformly distributed in a volume of fallback and ejecta material equal to the volume of the true crater.

Figure B-2[7] shows the variation of the ratio of the gamma dose rate at times greater than one hour after detonation to the gamma dose rate at H+1 hr. for various yield explosives as a function of time after detonation. Figure B-3[7] presents external gamma dose data based on the time of reentry of personnel into a gamma radiation field and on the H+1 hr. dose rate at the point of interest.

Figure B-4 and B-5[7] show the radioactive cloud dimensions and the equivalent fission yield in the cloud and fallout as a function of yield. Figure B-6[7] is based on the data obtained from the Danny Boy event and shows the gamma dose rate at H+1 hr. as a function of distance from surface ground zero.

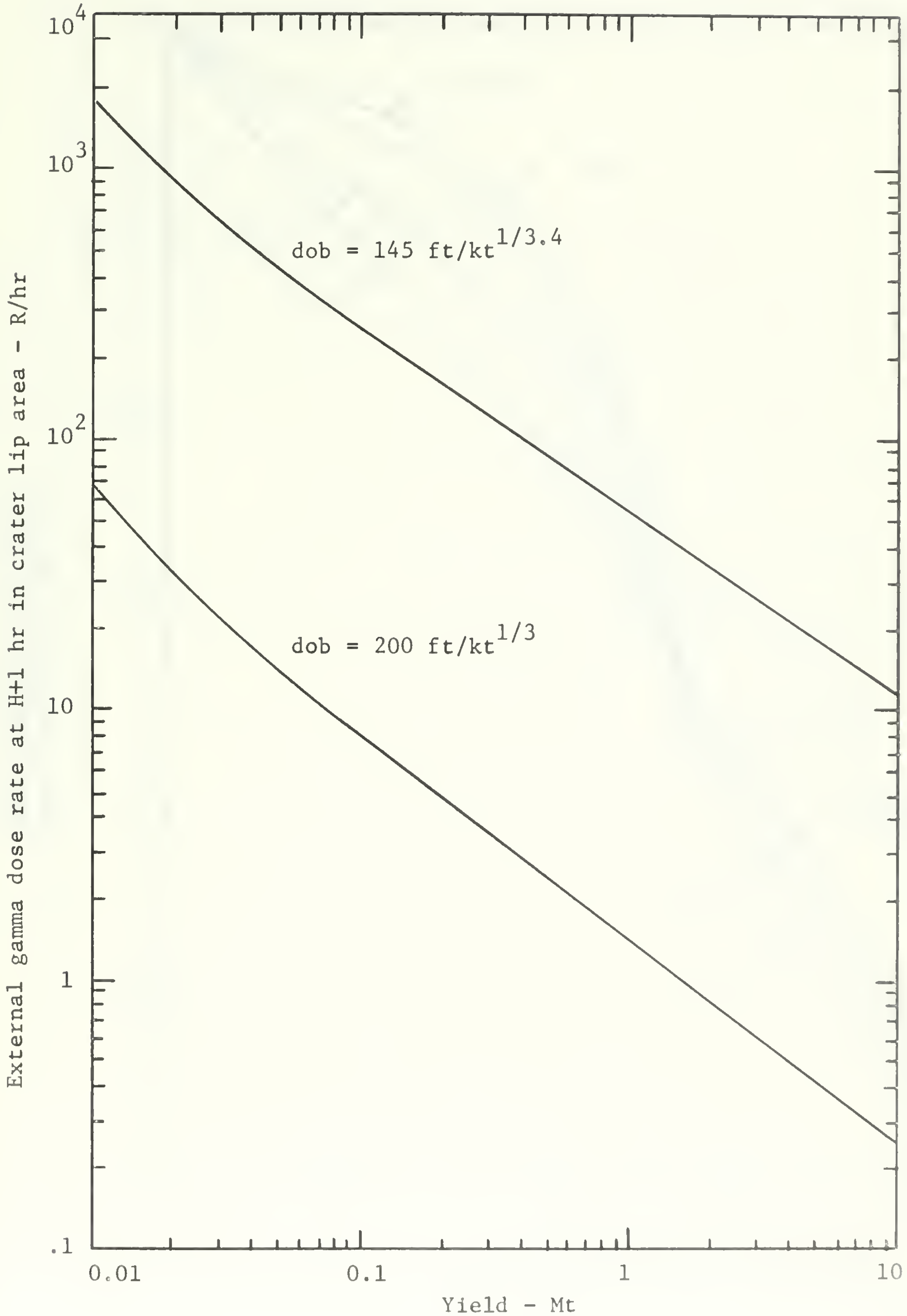


Figure B-1 External Gamma Dose Rate at H+1 hr in Crater and Lip Area as a Function of Yield and Scaled Depth of Burst

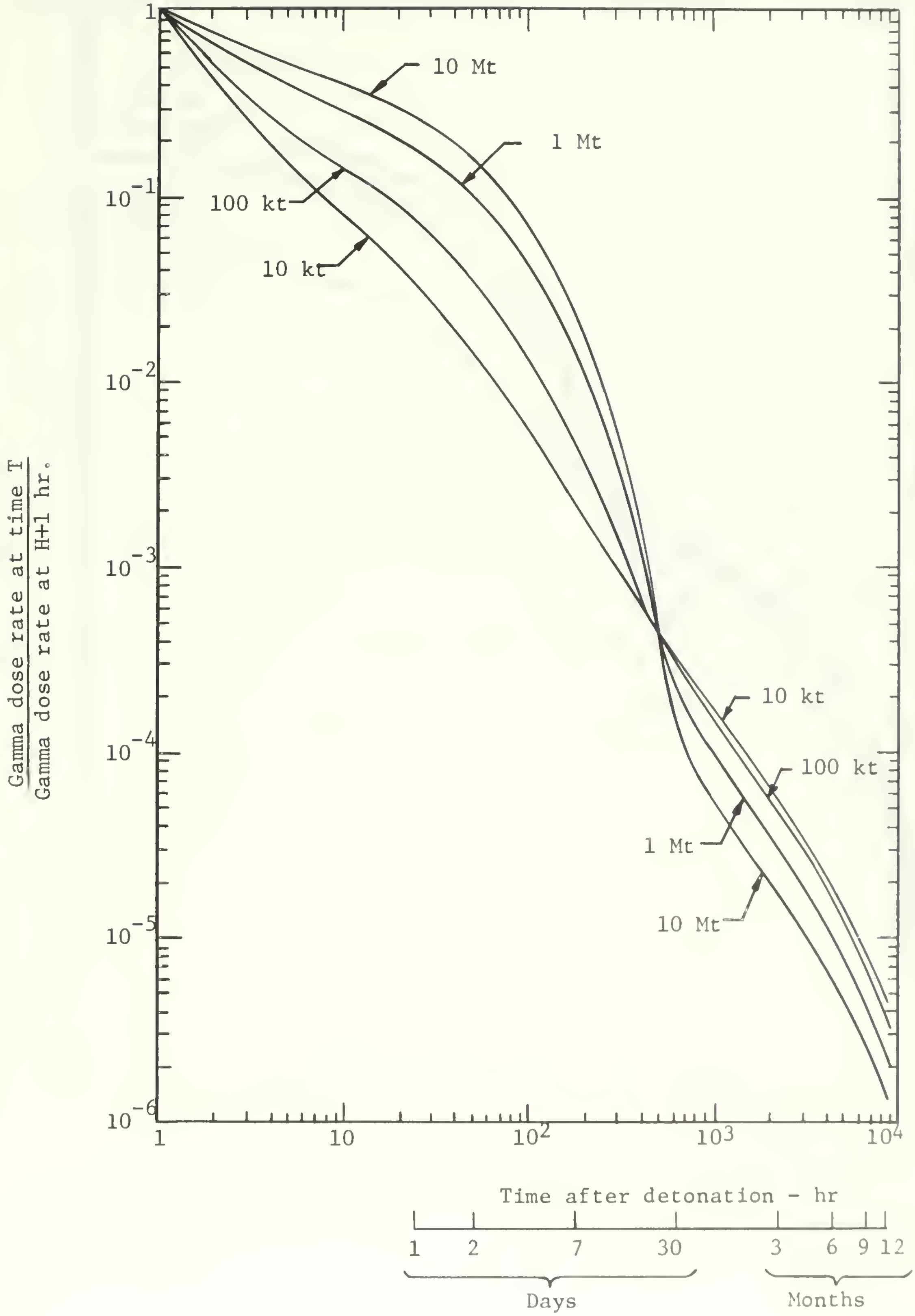


Figure B-2 Gamma Dose Rate as Function of Time Relative to Gamma Dose Rate at H+1 hr.

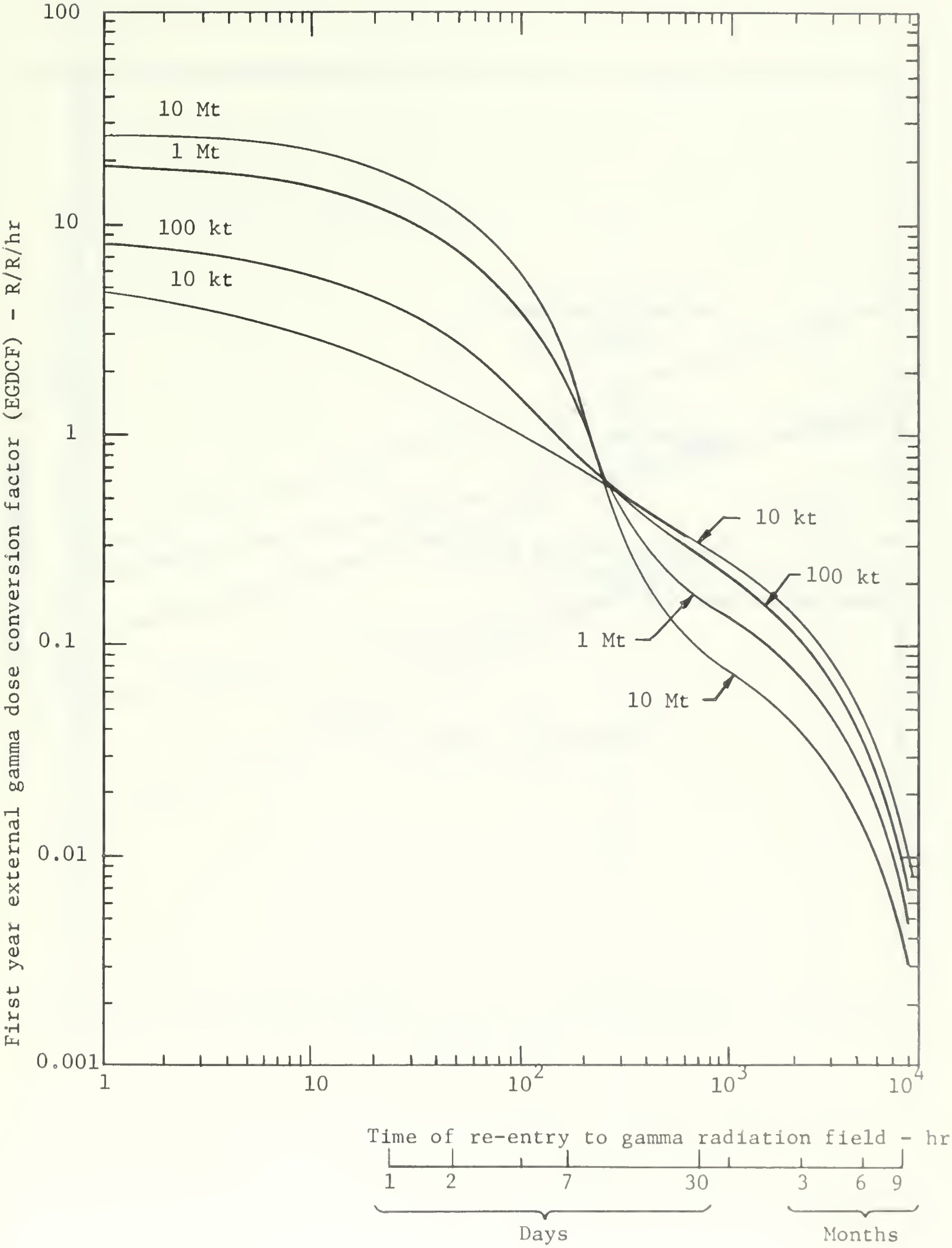


Figure B-3 External Gamma Dose Conversion Factor as Function of Reentry Time to Gamma Radiation Field

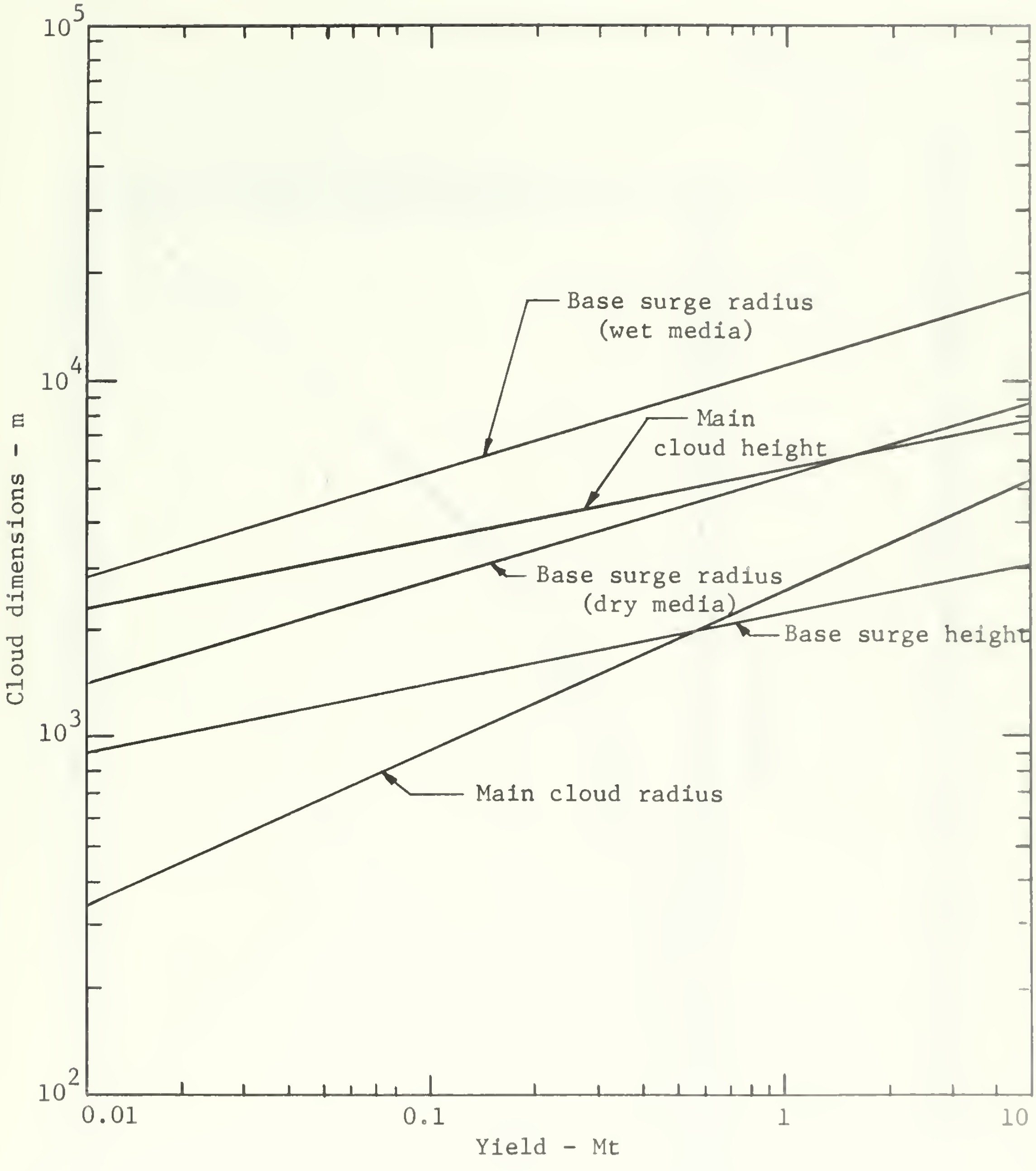


Figure B-4 Cloud Dimensions as a Function of Total Yield

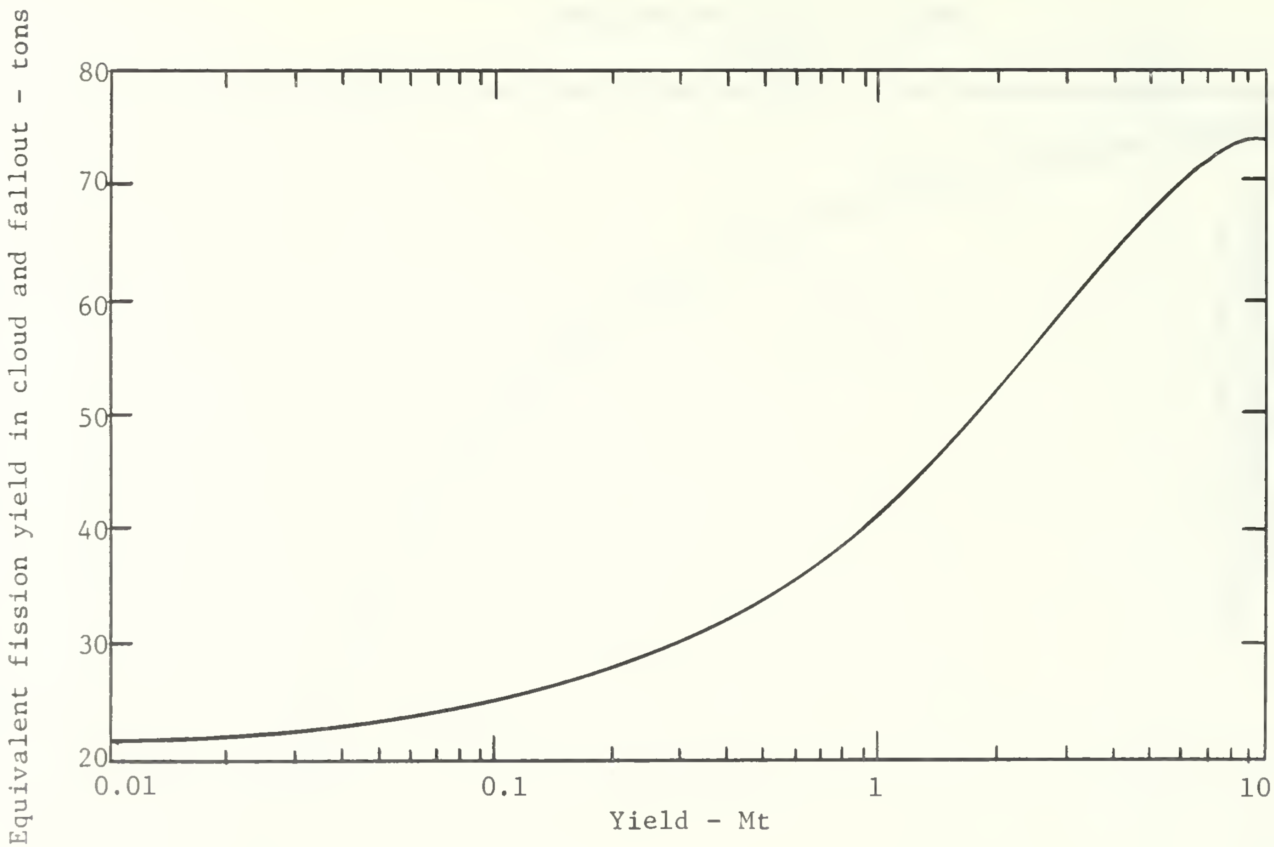


Figure B-5 Equivalent Fission Yield in Cloud and Fallout as a Function of Yield

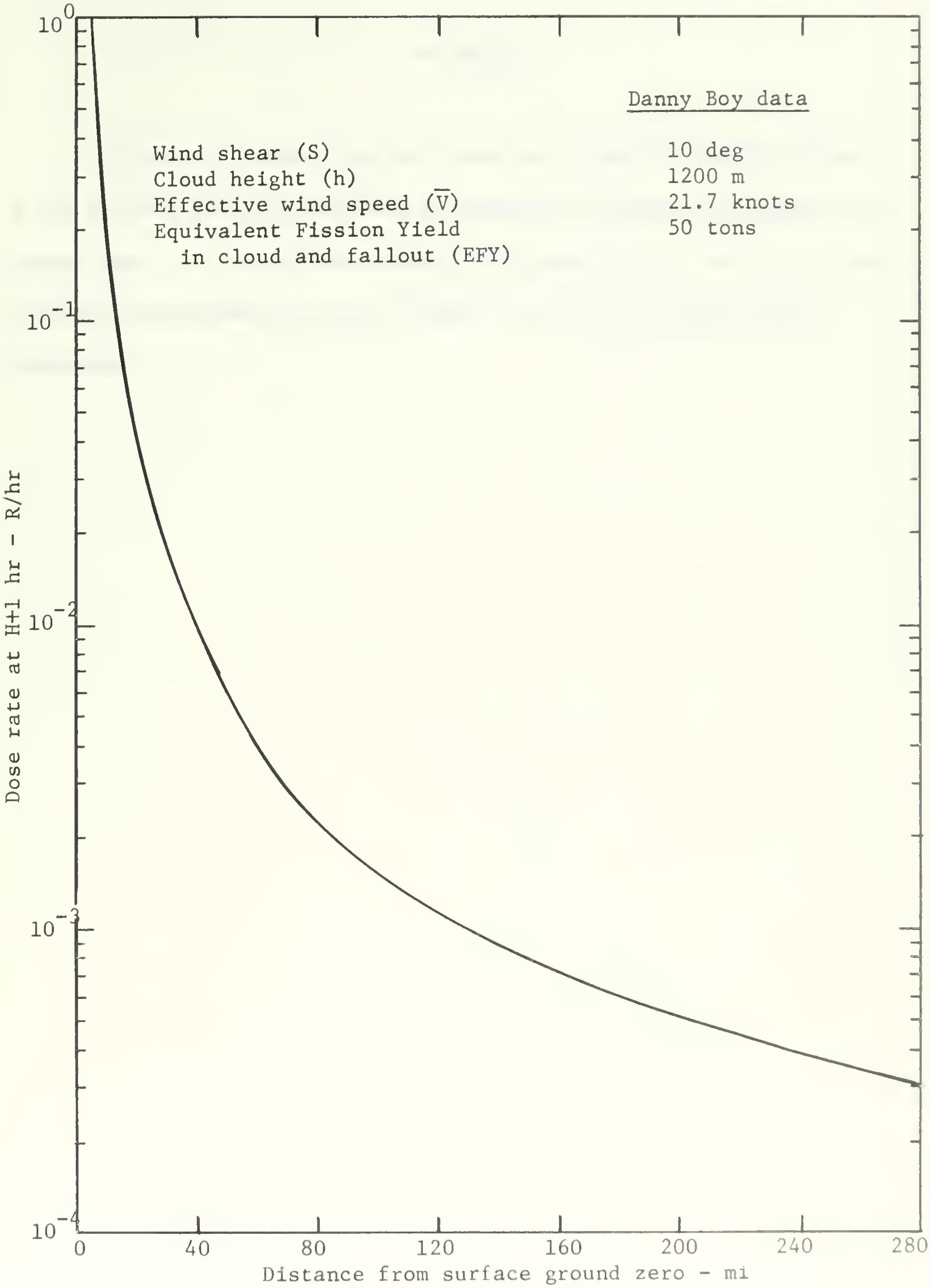


Figure B-6 Weather Bureau Scaling Curve

APPENDIX C

Figure C-1[7] shows the air blast overpressure resulting from a one kiloton free air burst as a function of distance (range) from ground zero. By using the scaling relationship shown on the figure, airblast overpressures for any other free air burst yield may be determined.

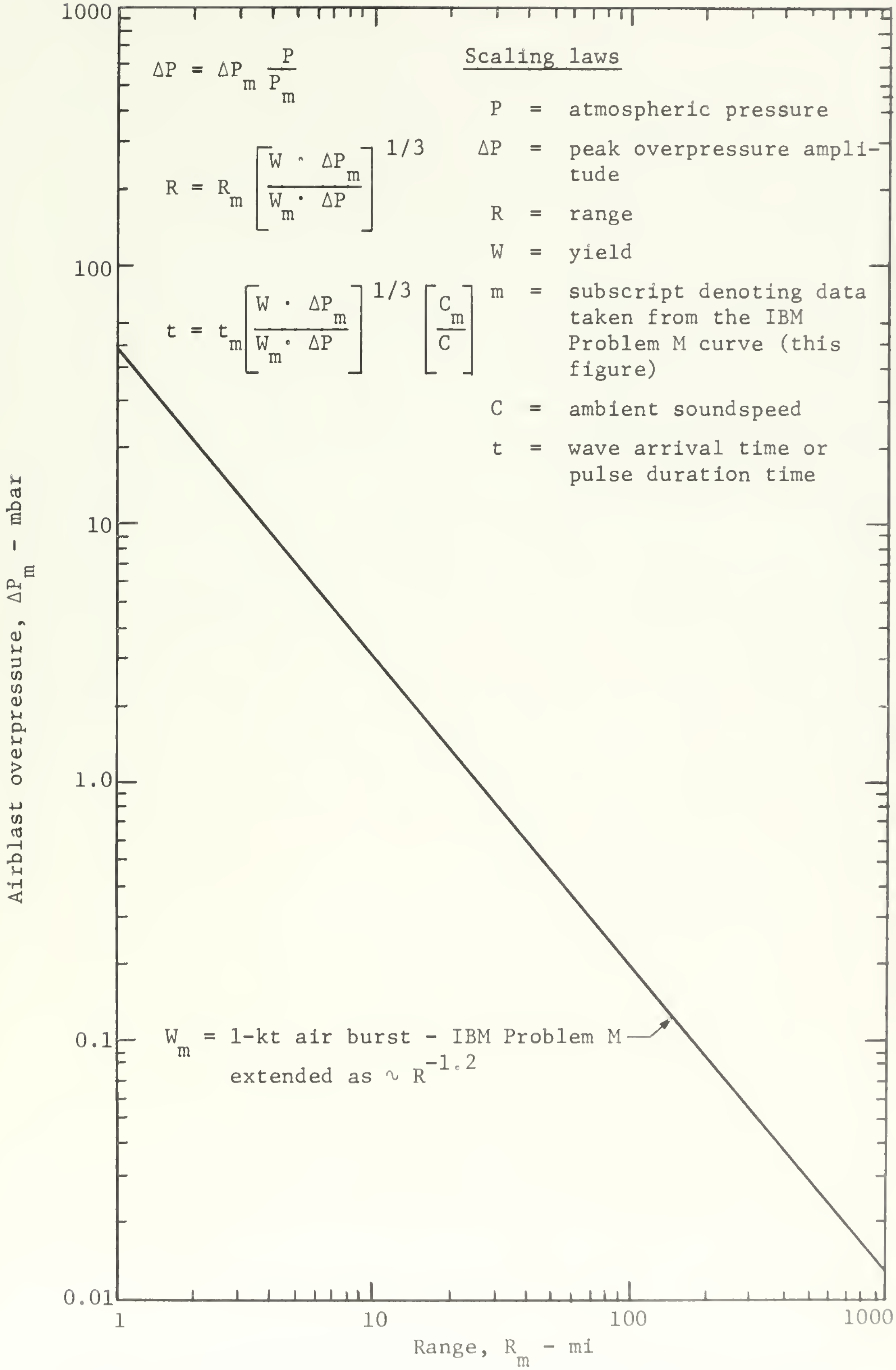


Figure C-1 Overpressure vs. Range - 1-kt Free Air Burst (IBM Problem M)